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APPLICATION OF THE SHORELINE INSTABILITY MODEL ALONG THE WESTERN SIDE OF THE CHESAPEAKE BAY, VA

A Thesis

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Masters of Science

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by

Kevin G. Skunda

2000

APPROVAL SHEET

This thesis is submitted in partial fulfillment of

the requirements for the degree of

Master of Science

Kevin G. Skunda

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ABSTRACT

Shoreline instability is influenced by numerous factors, many of which are physical in nature (e.g. waves, tides) or based on how exposed the shoreline is to the water. Other factors influencing shoreline change include bank characteristics and shoreline armoring. The theoretical Shoreline Instability Model (SIM), which combines the relative influences of some of the factors resulting in shoreline instability, was created with the help of Geographic Information Systems (GIS). The purpose of the SIM is to make what normally would be a subjective assessment of shoreline condition a more objective one by "parameterizing" these influences. Such consistency would be beneficial to coastal managers in the review of permits for altering the shoreline and could lead to future guidance in shoreline management.

Of the many factors influencing shoreline instability, six were chosen for inclusion in the model and each was given equal weighting initially. The six factors are: wave power, nearshore bathymetry, nearshore morphology, shoreline exposure, bank height, and bank vegetation. Wave power and nearshore bathymetry are both continuous variables with values relative to the maximum found in the study area. The remaining parameters are calculated as a percentage of a maximum condition. Conditions leading to greater instability are given higher percentages. The final instability rating is calculated by adding up individual shoreline instability ratings for each of the six factors and dividing by the number of parameters (6).

The study area used for the analysis was the western side of the Chesapeake Bay, VA. This area includes shoreline along the Rappahannock, Piankatank, Ware, and Poquoson Rivers, and Gwynn Island. Data for the wave power and nearshore bathymetry parameters were collected for locations 0.5 km apart within each study area using AML (Arc Macro Language) programs in ARC/INFO. Data for bank height, bank vegetation, and nearshore morphology, taken in the field using hand-held GPS units, was then transformed into GIS coverages for the analysis. The shoreline exposure parameter was determined for each location by counting the number of significant fetch directions.

Calibration of the model was first accomplished using a Principal Components Analysis using the statistical software SAS. This analysis revealed that two independent factors appear to be influencing the hypothesized shoreline instability rating. Two principal components were found to be significant. In the first PC, the three parameters related to offshore physical processes (wave power, nearshore bathymetry, and shoreline exposure) were significant, while in the second PC the three parameters related to bank characteristics (bank height, bank cover, and nearshore morphology) were significant. Multiple regression analyses were then utilized to compare the accuracy of the predicted instability factors with rates of shoreline change. Such rates were found by overlaying the digitized shorelines from 1994 Digital Orthophoto Quarter Quad (DOQQ) images and 1937 aerial photos of the study areas, calculating the distance between the shorelines and dividing by the number of years between photos (57). These analyses revealed that the model worked best with only the three offshore process parameters, and with wave power given twice the weighting as the other two parameters.

APPLICATION OF THE SHORELINE INSTABILITY MODEL ALONG THE WESTERN SIDE OF THE CHESAPEAKE BAY, VA

INTRODUCTION

Despite the aesthetic and recreational benefits of living along an estuarine shoreline, owning property on these lands can be rather hazardous. Each year many property owners along estuaries watch as their shorelines erode, mostly due to strong storms and the relative rise in sea level. Even though the erosion process may be gradual in most cases, some low-lying coastal areas experience flooding and significant land loss on a yearly basis. Current records reveal that the sea is presently rising on the order of only 2 to 3 mm/year (Komar, 1983). An increase in the magnitude of sea level rise is possible in the future, however, as a result of the greenhouse effect and global warming. Such an increase, coupled with increased storm activity, could lead to significant shoreline erosion in the years to come.

While sea level rise affects the coastal zone on a long-term basis, numerous other physical parameters such as waves, tides, and currents can cause noticeable changes to shorelines each season. Residents along the gently sloping East Coast are familiar with the detrimental impacts to the shoreline caused by hurricanes and winter storms known as northeasters. Erosion is a problem along the Pacific Coast, as well, despite the protection of its high bluffs and coastlines. The much higher wave climate along this coast of North America results in severe erosion on many stretches of shoreline.

Storm waves have the greatest effect on shoreline change due to the high energy released upon impact with the shoreline. Large fetches, or distance over a body of water that wind can blow, give rise to high-energy waves that strike the coastline. These waves lead to the erosion and entrainment of sediment, while longshore currents transport the sediment along the coast. Open ocean shorelines tend to receive the brunt of wave activity as a result of the extremely large fetches and deeper water nearshore. The shallower depths and smaller fetches of estuarine systems result in weaker wave environments. Estuarine systems, however, are influenced by tidal currents. The daily ebb and flood of the tide causes localized erosion or accretion of sediment along estuarine shorelines. These effects are especially noticeable at the entrances to harbors as well as tidal creeks (Hardaway and Anderson, 1980).

The fate of the nation's shorelines depends not only on Mother Nature, but on human behavior as well. A recent population influx into coastal regions over the past few decades has led to rapid development along shorelines. Such development has resulted in a loss of wetlands, a deterioration of water quality, and the alteration of the natural state of the shorelines. Within Virginia alone, tidal shorelines encompass over 5,000 miles along the Atlantic Ocean, Chesapeake Bay and its tributaries (Hardaway and Anderson, 1980). Over half of all Virginians live in the coastal plain and estimates for future populations figure on a sharp increase in population density in the Tidewater region (Mason, 1993). An increase in population will place even more emphasis on managing the already overdeveloped shorelines.

In 1972 Congress passed the Coastal Zone Management Act (CZMA), which provides assistance to coastal states in protecting the coastal zone. Through the National Oceanic and Atmospheric Administration (NOAA) federal monies are made available to states that have devised and implemented acceptable coastal programs. The Virginia Coastal Resource Management Program was approved in 1986 and exists as a network of several resource management activities administered by various state agencies. Within Virginia, the Department of Environmental Quality (DEQ) serves as the lead state agency in determining the distribution of grant money to the various agencies. This state agency receives all of the proposals for grant money under the CZMA and then forwards the recommended proposals to NOAA for final approval (Mason, 1993).

The Virginia DEQ also serves as the lead agency in the review of federal activities in the state's coastal areas. Under Section 301 of the CZMA, federal activities must be consistent with the state's coastal zone management program. If a federal activity within the state's coastal zone is found to be inconsistent with the state program, the state may prevent the federal activity. Some federal activities that fall into this consistency clause include dredging, navigation projects, and dams (Mason, 1993). Non-federal projects within the coastal zone of Virginia undergo a lengthy permit review process. Agencies at the local, state, and federal level are involved in reviewing the proposed activity before issuing their respective permits.

The review of a proposed project usually involves a site visit and, if applicable, follow-up investigations. Tools such as surveying techniques and aerial photography, as well as maps and charts, help coastal managers determine the shoreline condition and the threat of instability due to the proposed alteration of the site. In the past, however, coastal managers assigned to determine the effects of shoreline conditions have often done so in a haphazard fashion. Site inspections have usually been performed without understanding the temporal and spatial parameters involved in the dynamic nature of the shoreline. These parameters, as well as management options, are integral factors when considering the stability of a shoreline. Neglecting the effects of any one of these factors could result in a poorly managed shoreline and severely eroding bank conditions.

Some agencies such as the United States Army Corps of Engineers (Corps) have turned to computer models and high-tech equipment such as the CRAB (Coastal Research Amphibious Buggy) to analyze shoreline conditions. Such tools assist in measuring wave activity and sediment transport, thereby allowing coastal managers to predict the impact of the structure or activity on the shoreline. These models have already been applied extensively to open ocean shorelines. They tend not to work well, however, in an estuarine environment since data necessary to calibrate many of these models are not available for shallow water habitats.

The purpose of this Masters of Science thesis research is to develop the Shoreline Instability Model (SIM), which is a model similar to those used by the Corps that is able to characterize and predict the fate of a particular reach of estuarine shoreline as stable or unstable. Unlike the models developed by the Corps, however, the SIM will not require the input of numerous physical parameters and will rely more on observations of present shoreline conditions. The intended users of this model are both private and governmental coastal managers during the shoreline permit review process. Use of the SIM will make what normally is a subjective assessment of a shoreline's condition into a more objective one by "parameterizing" the relative influences on the shoreline.

REVIEW OF THE LITERATURE

Coastal Zone Management in Virginia

Activities along shorelines and tidal wetlands in the state of Virginia are regulated under the Virginia Wetlands Act (Title 28.2, Chapter 13) of 1972. Examples of regulated activities include the development and/or alteration of a shoreline. Such activities require the issuance of a set of permits before the project can be initiated. Certain activities (e.g. noncommercial piers, fences, normal road maintenance and outdoor recreation), however, are excluded from the permit requirement (Mason, 1993).

As a result of the 1972 Wetlands Act, localities that want to regulate their own tidal wetlands have the option of creating a wetlands board (WB) and adopting a model wetland ordinance found within the Act. The Virginia Marine Resources Commission (VMRC), which serves as the regulating entity for coastal resources in the state, has many duties including overseeing the local WBs. Another duty of the VMRC is to serve as the legislative body for those localities choosing not to form their own WBs. Finally, the VMRC hears appeals from landowners regarding decisions made by local WBs and renders a verdict to either overrule or back the board's decision (Bradshaw, 1995).

In addition to serving as the regulating entity of local WBs, the VMRC has the duty of protecting the states' bottom or subaqueous lands out to the three-mile limit. Under the Subaqueous Law, it is unlawful to conduct activities in the waters of Virginia without a permit from the VMRC. Activities such as dredging as well as the construction of wharfs, commercial piers and marinas require a permit under this law. Since Virginia law provides private landowners ownership of their land out to the Mean Low Water (MLW) mark, state jurisdiction under this provision occur channelward of MLW. In nontidal waters, jurisdiction applies to areas channelward of ordinary high water (Mason, 1993).

Any activity with the potential to affect coastal resources in the Tidewater region requires not only state and local permits, but a federal permit as well. The Norfolk District of the Army Corps of Engineers serves as the main federal legislating body in Virginia. Under the Rivers and Harbors Act of 1899, any activity within the coastal region to the point of MHW is subject to review by the Corps (Bradshaw, 1995). The Act, as well as Section 404 of the Clean Water Act (CWA), gives the Corps the same jurisdiction in the coastal zone that the Subaqueous Law gives to the VMRC. Section 404 of the CWA states that a permit must be obtained from the Corps for any dredge or fill activity in the waters of the United States (Mason, 1993).

Also under the Clean Water Act, Section 401 allows states to administer a certification program in conjunction with the Corps' Section 404 Permit review process. In Virginia, the DEQ's Water Quality Division administers the certification program, which is now known as the Virginia Water Protection Permit Program (VA Code Sec. 62.1-44.15). The purpose of the Section 401 Permit is to ensure that surface water quality will not be degraded by construction activities or similar development within the coastal zone, especially wetlands. Permits must be issued for activities resulting in discharges to surface waters subject to tidal influence. Types of activities exempt from the permit requirements include such things as the placement of navigation aids, fish and wildlife harvesting devices, and noncommercial mooring buoys, as well as survey activities (Mason, 1993).

The first step for the landowner in obtaining the necessary permits is to fill out a joint permit application and return it to the VMRC. A copy of the completed application will then be sent to the other agencies involved in the process, including the Corps and, if applicable, the local Wetlands Board. Applications are processed independently by each group. Other advisory groups such as the Virginia Institute of Marine Science (VIMS)

Wetlands Group, the Virginia DEQ, the Environmental Protection Agency (EPA), the National Marine Fisheries Service (NMFS), and the Fish and Wildlife Service (FWS) each receive copies of the application from their respective state or federal lead agencies. These groups provide technical support and advice on the proposed application throughout the process (Bradshaw, 1995).

Corps, VMRC, and/or local WB permits are all required for activities in the state's wetlands, subaqueous beds, sand dunes, and beaches. Activities which may require permits include dredging, filling, and the construction of erosion control devices such as groins, bulkhead and riprap (Bradshaw, 1995). At the end of the permitting process, the landowner should have three permits for the same project. If one of the agencies denies the granting of a permit, the project can not occur. Similarly, one permit may place conditions on the project different from another permit. If this situation occurs, the landowner must obey the most restrictive permit in order not to violate the other permits. Failure to follow any of these conditions can result in hefty fines or even cancellation of the existing permits (Barnard, 1998).

While the permitting system in the state of Virginia is rather complex, some states have successfully streamlined their permitting process to make it more efficient. For example, in North Carolina, the Division of Coastal Management (DCM) set up the Coastal Resource Commission to handle the permit process. North Carolina's permit program, established under the Coastal Area Management Act (CAMA), became effective in 1978 and requires permits for development in Areas of Environmental Concern (AEC). An AEC is an area of natural importance that may be destroyed easily by erosion or flooding. Examples of the types of regulated activities in an AEC include the dredging or filling of coastal wetlands or waters as well as the construction of marinas, piers, bulkheads or other structures along a shoreline (NCDCM, 1999).

Three types of permits can be issued in North Carolina: major permits, general permits and minor permits. Major permits are needed for activities that require other state or federal permits, for projects that cover more than 20 acres or for construction covering more than 60,000 square feet. Applications for major permits are reviewed by ten state and four federal agencies before a decision is made to grant or deny the permit. General permits are used for routine projects that usually pose little or no threat to the environment. Minor permits are used for projects such as single family houses that do not require other permits.

Coastal zone projects are reviewed, issued and administered to CRC standards by local governments under contract with the DCM. Approximately 700-900 minor permits are issued each year by local governments. Using the minor permit program helps to minimize the burden on permit applicants as well as the CRC. Under CAMA regulations, a minor permit is to be issued within 25 days once an application has been completed. Such a regulation ensures both a rapid review and timely approval or denial of the proposed project (NCDCM, 1999).

In addition to regulating development, the CRC has recently focused on shoreline stabilization due to a recent understanding of the damage that bulkheads and other structures inflict on ecologically important areas. Current regulations require that riprap and gabions be used preferentially over bulkhead to stop erosion along a shoreline, but no regulation prohibits the use of bulkheads. Under newly proposed regulations, however, bulkheads will only be allowed if the property owner can prove that nonstructural methods will not be enough to solve the erosion problem. Regardless of whether the new regulations are adopted, North Carolina has at least drawn attention to the risks of using bulkhead and has made attempts to steer landowners towards using other methods of erosion control (CAMAgram, 1998).

Shoreline Erosion

Erosion along a stretch of shoreline occurs as a result of a complex interaction of physical processes. Waves, tides, and nearshore currents interact to entrain and move sediment along and offshore (Komar, 1983). Shoreline erosion on a daily basis is minimal, but can be substantial over the course of the year. Severe erosion along the East Coast of the United States occurs as a result of high energy tropical storms (i.e. hurricanes) and extratropical storms (i.e. northeasters). Erosion rates vary from year to year, but are influenced by: 1) the frequency of storms; 2) the type and direction of storms; 3) storm intensity and duration; and 4) the resultant winds, tides, currents, and waves (Hardaway, 1980).

The generation of waves in a body of water depends on the speed and duration of the wind as well as the fetch area. Longer wind durations and larger fetches result in greater amounts of energy being transferred to the water, which can be seen through the development of waves. As the wind begins to blow across a body of water only small ripples are formed with periods less than one second and heights of only a couple of centimeters. If the wind continues to blow, waves with longer periods will form and join the already present smaller ripples. These waves have longer wavelengths, which allows them to increase in size without breaking. As waves approach shore, adjacent wave crests converge and become narrower and peaked while the troughs widen and flatten. Eventually the waves reach maximum steepness, become unstable, and break onshore. Waves with larger wave heights break in deeper water than waves with smaller wave heights (Komar, 1983).

Waves that strike a shoreline at an angle set up what is known as a longshore current, which moves parallel and adjacent to the shore. The movement of sand in the littoral zone can either be parallel to shore, onshore or offshore. In most systems, there is a net movement of sediment in one direction along a shoreline. Beaches are natural landforms resulting from wave action, and represent a buffer zone between land and water. During storm periods, waves can carry much of the beach sands offshore to form a bar. Bars help dissipate wave energy before it reaches the shore. As calmer weather returns, the bar sands will then slowly migrate back towards the beach (Hardaway, 1980).

While the impact of waves on the shoreline during a storm often cause the majority of the observed erosion, tides and storm surge can also influence shoreline change. High tides can lead to flooding of low-lying coastal areas, inundating the normal surf zone, and attacking the upland directly. Tidal currents are generated by the periodic rise and fall of the astronomical tide. Twice each month (during new and full moon) the earth, moon, and sun align so that the forces of the moon and sun combine to produce increased tidal ranges called spring tides. If a storm occurs at a time of spring tides, inundation and flooding is greater and the threat to coastal property is greater. Worse yet, if the storm occurs during perigean spring tide (spring tides plus the moon is in its perigee position) high tides will be elevated to a level an extra 40% above normal (Komar, 1983).

The effect of storm surge can be as harmful as spring tides to coastal owners. Storm surge is the rise in water level due to strong onshore winds and a drop in atmospheric pressure from the storm. The additional amount of water pushed onshore will add to the already high water level and increase the chance of coastal flooding. Extremely low pressures that can occur during both tropical and extratropical storms can further increase water level by using the ocean surface as an inverse barometer. As the pressure within the storm decreases by one inch of mercury, the water level rises approximately thirteen inches. Storm surge has the potential to raise water levels by several meters above the highest high tides which are normal for a coastal area thereby covering areas that are not usually affected by wave attack. Considerable destruction can occur from the large waves superimposed on the high water levels since shoreline structures are generally no longer effective under these extreme circumstances (Komar, 1983).

In addition to physical processes, the presence of man-made structures such as bulkheads and groins has the potential to modify the erosion process. Property owners along receding shorelines often turn to coastal protection devices in order to shield their homes from the threat of erosion. One course of action for these property owners is to use "soft" stabilization methods. Such methods help by retaining sediments and preventing shore as well as upland erosion. A few examples of "soft" stabilization methods are beach nourishment and bank vegetation. These methods will often suffice in lower energy environments such as along some of the tidal tributaries of the Chesapeake Bay (http://superior.lre.usace.army.mil/shore.protection).

When wave energy is high along an estuarine shoreline, however, "hard" erosion control structures such as riprap and bulkheads are usually installed. These defense structures hold up well in most conditions and limit the amount of erosion, but they often cause detrimental effects to adjacent or downdrift shorelines. "Hard" erosion control can also be accomplished with the use of offensive hard structures such as groins or breakwaters. These structures are constructed in order to contain sediment in a particular area or to collect sediment that would normally be transported offshore. Groins and breakwaters are most often successful when they are used in low to moderate energy environments in addition to using beach nourishment as a method for controlling shoreline erosion (http://superior.lre.usace.army.mil/shore.protection).

The Chesapeake Bay Estuarine System

The Chesapeake Bay, a drowned river valley of the ancestral Susquehanna River system, is the largest estuary in the United States. Its shoreline is highly irregular consisting of many tributaries and embayments. The major tributaries of the Chesapeake Bay are the James, York, Rappahannock and Potomac Rivers, each of which is dissected by numerous tidal creeks. These shorelines have suffered through severe erosion over time as a result of elevated wind and wave climates from high energy storms in addition to human modification of land use (Hardaway et al., 1992).

From 1850 to 1950, the Virginia part of the Chesapeake Bay system lost over 21,000 acres of land to shoreline erosion. Areas particularly affected include the bay side of the Eastern Shore, the western shore of the bay and the south shore of the western tributary estuaries. The high historical erosion rates along these shorelines can be attributed to shoreline exposures to the north, northwest, and northeast. Shorelines with these exposures face in the direction of the strong winds from northeasters (Hardaway et al., 1992).

Virginia has not always had such an extensive estuarine system threatened by erosion. About 15,000 years ago, the coastline of Virginia was about 60 miles east of its present day location and water level was some 300 feet lower. The coastal plain was broad and low, while the estuarine system was a meandering series of rivers working their way to the coast (Hardaway, 1996). Water was locked up in glaciers covering the northern half of North America. As the glaciers began to recede in response to a gradually warming climate, the melt waters began to raise the level of the ocean. The rise in sea level caused the shoreline and estuarine system to slowly migrate upward and westward across the continental shelf (Hardaway, 1980). As the sea level rose, these rivers began to get inundated. This inundation caused the shorelines of the estuarine system to recede. Shorelines have continued to recede since that time even though sea level rise has slowed considerably over the years. The seasonal occurrence of tropical and extratropical storms, however, has been responsible for much of the recent shoreline erosion (Hardaway, 1996).

The major shore types in the Chesapeake Bay system associated with the latest transgression are marsh and upland banks, with some dunes, beaches, and spits. Marshes occupy the fringes of water bodies and low regions of coastal systems bayward of upland regions. They grow vertically and laterally landward in response to sea level rise (Hardaway, 1996). The marsh acts as an effective buffer to erosion of the upland. Its low elevation and matted root system make it resistant to wave action. Extensive marsh systems alleviate the threat of flooding in coastal areas, whereas fringing marshes along sediment banks greatly reduce wave action and slow down the erosion process along the shoreline (Hardaway, 1980).

Sediment banks are composed of variable mixtures of gravel, sand, silt and clay. They range in height from a few feet to tens of feet above MHW. Higher banks (>15 feet) exist along the lateral tributaries and on the bay side of the Eastern Shore. Erosion of high banks occurs as a result of excessive rainfall and saturation due to groundwater. This results in slumping and an unstable bank condition. Wave action during storms causes further instability by undercutting the base of the high bank. Low sediment banks (<15 feet) can be found along the small creeks and embayments on the western side of the Chesapeake Bay. High waves during storms overtop low banks and carry off large pieces of upland. Planting vegetation on these banks often reduces some of the problems of erosion (Hardaway, 1980).

Erosion of upland banks typically will provide additional sediment into the overall estuarine system. The impact of waves on the shoreline acts to remove the sediment and results in the formation of a sand beach along the base of the bank. A similar process is carried out by tidal currents, which help in the formation of a spit. This land formation is an extension of sand that moves across the mouth of a lateral creek in an estuarine system. Often times vegetation will colonize these newly created substrates and will aid in the stabilization of the unconsolidated sediments (Hardaway, 1996).

The underlying geology is a major factor in the height of the banks along the Chesapeake Bay and its tributaries. The Suffolk Scarp, which is an old beach feature formed during a high stand in sea level two million years ago, runs the length of the Virginia coastal plain along the western side of the Chesapeake Bay. West of the Suffolk Scarp the shoreline banks rise to heights of 25-50 feet. Other scarps to the west such as the Surry Scarp cause the land and shoreline banks to rise even higher. East of the Suffolk Scarp the land drops to areas that may be less than five feet above sea level and contain extensive marshes. These areas include much of the shoreline within the cities of Norfolk, Hampton, and Poquoson and the counties of York, Gloucester, Mathews and Middlesex (Hardaway, 1996).

Shoreline Studies

The VIMS Center for Coastal Resource Management has played an active role in both studying and managing estuarine shorelines for the Commonwealth of Virginia since the passage of the Clean Water Act and the Coastal Zone Management Act in 1972. The Center uses shoreline inventories to relay information to state managers, planners and regulators. Information on the condition of the immediate riparian zone is collected in the field, processed at VIMS with the help of remote sensing data, and displayed using Geographical Information Systems (GIS) maps within Shoreline Situation Reports for each county.

Using GIS and remote sensing, historic trends of shoreline change can be calculated on a reach by reach basis. Such a calculation can be performed through comparing shoreline positions from aerial photos of various years. Methods other than the more technologically advanced ones just mentioned also exist to examine shoreline change. Surveying is a popular method of coastal managers due to its high accuracy. The high costs and time-consuming nature of this method, however, makes this option unpopular for those wishing to make numerous records over a short period of time. Maps and charts are one of the easiest and cheapest methods available, but their drawbacks include low accuracy and resolution as well as the high cost for creating new maps. Nevertheless, existing maps and charts are one of the few ways to get good historical data as far back as the 1800s (Dolan et al., 1983).

In general, coastal managers will use many of these methods in determining shoreline retreat rates and past shoreline conditions. Often they will use ground level surveys to provide the highest quality shoreline data in site-specific areas. Maps and charts will typically be used to determine regional trends in shoreline retreat. Remote sensing is a new tool in analyzing data and is starting to be used extensively. From these data, coastal managers can learn about past and present conditions of a stretch of shoreline and extrapolate that data to predict future conditions. Usually, however, these future predictions are based on best professional judgment and lack much in the way of any type of scientific certainty (Dolan et al., 1983).

The current trend in some federal and state agencies is to use numerical models with the aid of computers to study coastal processes at a given site. The Coastal Engineering Research Center (CERC) of the Army Corps of Engineers (Corps) in Vicksburg, Mississippi has been at the forefront in developing this technology. Over the years the Corps have applied many models to specific engineering projects along the coastline, especially to ones requiring some level of beach nourishment. The overall complexity of some of these numerical models, however, results in a significant amount of data input as well as effort in order to be applied to real world situations (Cialone, 1992).

Researchers at CERC have focused mainly on two types of models: 1) beach erosion models, and 2) shoreline change models. Simple beach erosion models calculate sand loss on the upper profile resulting from storm surge and waves. Longshore sand transport processes are omitted so that only one profile at a time is analyzed. Also, the model assumes an equilibrium beach profile that is maintained or eventually achieved following a change in water level. This assumption was included to prevent the nearshore profiles from becoming progressively steeper or eventually attaining unreasonably low gradients (Kraus, 1990).

SBEACH (Storm-Induced Beach Erosion) is an example of a beach erosion model used by researchers at CERC. The model predicts storm-induced beach erosion by simulating the formation and movement of sandbars and berms. SBEACH assumes that morphological changes near the surf zone occur from breaking waves. Wave height, period, water level, beach grain size, and initial profile shape are all required parameters for the model. Using these parameters, SBEACH returns a beach profile as well as cross-shore distributions of wave height and water level at specified intervals. Not only can SBEACH accurately predict storm-induced erosion, it has been successfully used on beach fill projects to determine the extent of erosion after beach nourishment (Cialone, 1992).

Shoreline change numerical models function similar to beach erosion models. These models calculate shoreline response to wave action under a wide range of variables that vary in both time and space. The parameters used in these models include beach, coastal structure, wave, and boundary conditions. Extensive testing of shoreline change models suggests they can provide accurate predictions of shoreline change. Since the profile shape is assumed to be constant, onshore and offshore movement of sediment at any contour can be used to represent beach change. The contour line is usually considered to be the shoreline, however, because mean shoreline position is usually readily available to coastal managers (Kraus, 1990).

GENESIS (Generalized Model for Simulating Shoreline Change) is a one-dimensional model for simulating long-term shoreline change. The required input parameters include: "initial shoreline position, measured shoreline position for calibration purposes, structure positions, depths along the nearshore reference line, and the wave height, period, and direction for every time-step" (Cialone, 1992, p. 4). Values for these parameters can be obtained with the assistance of another program called RCPWAVE (Regional Coastal Processes Wave Propagation Model), which is a short-wave numerical model that uses linear theory to predict coastal changes resulting from natural forces and man-made structures. Results derived from RCPWAVE provide an accurate description of the physical processes at hand (Corps of Engineers, 1992).

After inputting data from either RCPWAVE or from field data collection, GENESIS returns shoreline position and longshore transport rates for the user-specified intervals. GENESIS works best in situations in which a systematic trend causes the long-term change in shoreline position, such as shoreline retreat downdrift of a groin. The Corps have used the model GENESIS to predict the response of the shoreline to erosion control structure modifications, long-term beach fill response, and beach nourishment projects. One drawback to shoreline change models, however, is that they are not applicable to highly fluctuating beach systems in which no trend in shoreline position is evident. These models also can not be applied to the interiors of inlets or areas dominated by tidal flow such as in estuaries (Cialone, 1992). Wave conditions in estuarine systems are typically difficult to model, while tidal currents and irregular bottom topography result in highly fluctuating parameters that the models can not effectively handle (Kraus, 1990).

Even though numerical models have been sparsely applied to estuarine waters, an attempt was made to predict shoreline conditions along the Chesapeake Bay in Virginia. In November of 1992, C. Scott Hardaway Jr. and others of the Virginia Institute of Marine Science developed a computer software program called SEASware. SEASware (Shoreline Erosion Assessment Software) evaluates shoreline conditions and provides a recommendation of whether a method of shoreline erosion control is needed. The program depends on the input of shoreline parameters and wave climate. Wave conditions are derived from the fetch distance (Hardaway et al., 1992).

The parameters selected for inclusion in SEASware were chosen on the basis of extensive research by O'Conner, Riggs and Bellis in the 1970's on shoreline erosion processes in fetch-limited, semi-enclosed seas of the Mid Atlantic region. This research resulted in the creation of the Chesapeake Bay Shoreline Erosion Potential Scale (CBSEPS) to assess shoreline erosion potential in terms of annual erosion rates. Different weights were given to each of the thirteen parameters and then values were found from maps, charts, and site visits. A final score of the cumulative values of each of the parameters determined the erosion potential at that site. This score, or the Shoreline Erosion Index (SEI) value, was intended to be used by shoreline owners, coastal managers, and policy makers in deciding whether to construct erosion control devices along a specific section of shoreline (Hardaway et al., 1992).

The thirteen parameters used in the SEASware evaluation are: 1) average fetch, 2) longest fetch, 3) depth offshore, 4) shoreline orientation, 5) shoreline geometry, 6) boat wakes, 7) bank height, 8) bank composition, 9) width of sand beach or intertidal low marsh, 10) width of backshore region or high marsh, 11) upland bank condition, 12) nearshore morphology, and 13) abundance of nearshore aquatic vegetation. Parameters at any reach of shoreline are considered to change with time, especially along shorelines with high erosion rates. There is a general trend, however, of finding higher shoreline erosion rates along more open shore reaches as well as those shorelines that face to the north (Hardaway et al., 1992).

Despite the relative simplicity of the SEASware program, local wetlands boards in Virginia have not been quick to use it in their decision-making process and do not appear to be adopting it anytime in the near future. Other Virginia coastal resource agencies currently do not use SEASware in their permit process either. A program or method similar to SEASware is needed, however, to provide guidance for shoreline management and to make the entire permitting process more consistent. At this time the models currently available apply only to open-ocean coastline situations. No model exists to handle the highly fluctuating environments in estuaries. This thesis will help to fill that void and provide coastal managers with a model to use in the analysis of shoreline instability on a reach by reach basis.

METHODOLOGY

Choice of Factors for the Model

A preliminary list of factors affecting shoreline stability, defined by the extent to which the position of the shoreline has changed over time, was formulated based on past experience and a review of the literature. Hardaway et al.'s SEASware formula was taken into account since the parameters used in that model also apply to estuarine systems. This preliminary list (seen in Table 1) focuses not only on physical parameters such as waves and tidal currents, but also on shoreline characteristics and natural phenomena such as bank conditions, storm intensity and storm frequency as well.

From the 20 parameters initially chosen, the parameters thought to be the most important to shoreline stability were selected for the Shoreline Instability Model. These primary factors are: 1) fetch, 2) nearshore bathymetry, 3) nearshore morphology, 4) bank height, 5) bank vegetation, and 6) shoreline exposure. Secondary factors affecting shoreline stability include tidal currents, bank composition, along-shore sediment supply, storm frequency and duration, and boat wakes. These factors, although important, were not included in the model. It was thought that the impact of these factors on erosion was periodic or difficult to quantify.

Fetch, or the distance of open water over which wind can blow and generate waves, has long been considered one of the most important predictors of the wave environment along a stretch of shoreline. Short fetches result in weaker wave environments striking a shoreline, while longer fetches produce the stronger wave climates that inflict severe erosion and instability of a shoreline. Therefore, shorelines that are shielded from wave attack will typically be more stable than open-ocean shorelines and shorelines along the mainstem of an estuary (Hardaway and Byrne, 1999).

Nearshore bathymetry, which describes the depth of the water immediately offshore, is another factor that contributes to the level of shoreline stability. Wide, shallow nearshore regions tend to dampen wave action through frictional attenuation better than a nearshore region with the same average fetch, but having deeper water offshore. Shorelines with deeper water offshore are exposed to stronger wave climates and are more likely to suffer from instability problems than shorelines with a shallow nearshore region (Hardaway and Anderson, 1980).

Protection of the shoreline from wave attack can also be accomplished with the help of natural features located along the shoreline. Nearshore morphology, or the presence of landforms such as beaches, marshes, and offshore bars, plays an integral role in determining shoreline stability. The presence of these natural buffers can be effective "erosion control" for the upland and minimize the need to install permanent devices such as groins, riprap or bulkhead. Without these natural buffers, waves have unimpeded access to the upland coast and strike the shoreline with the maximum force. Thus, non-buffered shorelines tend to have a greater likelihood for instability than buffered shorelines (Hardaway et al., 1992).

Bank height can also be an important predictor of shoreline stability. Low bank heights erode rapidly because waves come into contact with more of the upland, while higher bank heights provide the upland with a greater protection from wave energy. The lower erosion potential of high banks also occurs as a result of sediment slumping from the upper bank to the base of the bank. This slumping can actually act as a buffer for a brief time. High banks can, however, suffer from instability over time when wave action is strong enough to undercut the base. Such a condition causes the sediment in the upper part of the bank to break off, fall, and get washed offshore (Hardaway et al., 1992).

The amount of bank vegetation is often another important predictor of the level of shoreline stability and is a good sign of the extent of recent shoreline erosion. Vegetation of the bank affects the ease in which waves remove sediment from the bank. Banks which are mostly vegetated are difficult to erode since the sediments are held together firmly by the root structures of trees, plants, shrubs and grasses. Non-vegetated banks, however, suffer from a greater threat of erosion in a given wave environment since the sediment is loosely compacted and therefore easier to remove by wave action (Hardaway and Anderson, 1980).

The final parameter, shoreline exposure, is based on the concept of shoreline geometry. Whether a shoreline is protected from or exposed to wave energy determines how much wave energy can potentially reach the shore. Intuitively, the more exposed a shoreline is to the water the larger the potential for instability. Thus, locations with waves reaching the shore from many angles have a larger potential cumulative wave energy approaching shore. This has to do with shoreline geometry in that headlands are more exposed and vulnerable to wave attack, while embayments are more protected. Headlands, therefore, receive greater amounts of wave energy than embayments and thus suffer from a greater likelihood of instability (Hardaway et al., 1992).

Calculation of Parameter Weights

For the Shoreline Instability Model, a level of instability was calculated for numerous shoreline locations along the western side of the Chesapeake Bay, VA. At each of the locations, values for the six parameters were determined or calculated. In order to reduce the bias of one parameter over another, the parameters were initially given equal weighting. A weight out of a maximum 100% was assigned to each of the six parameters to obtain a total weighting of 600%. A final instability factor was determined by dividing the total instability weighting (out of 600%) by the number of parameters (6), thus providing a percent weight for the extent of instability at a given location. Weighting each parameter was performed in a manner such that shorelines with parameters favoring more stable conditions had low instability factors while shorelines with parameters favoring more unstable conditions had higher instability factors.

The first parameter, wave power, is based on fetch distance. It also takes into account the effect of winds, however. Table 2 is data containing wind conditions at Norfolk International Airport from 1960 to 1990. Values are given for each of the eight directions on the wind rose (south, southeast, east, northeast, north, northwest, west, southwest) at various wind speeds (<5 mph, 5-11 mph, 11-21 mph, 21-31 mph, 31-41 mph, 41-51 mph). Readings were taken hourly during the 30-year time period and recorded as total occurrences in each category as well as a percentage of the total number of observations.

The wave power value for the model was weighted using this wind data. The first step in determining the wave power value was to use ARC/INFO in the calculation of a fetch distance. Fetch measurements were taken in units of meters for each of the eight directions on the compass rose. Distances falling over land were recorded as zero. This process was run using an AML (Arc Macro Language). Fetch distances found using this method were first converted to units of miles and then used to find significant wave heights at each of the wind speed mid-ranges (3 mph, 8 mph, 16 mph, 26 mph, 36 mph, and 46 mph) of the Norfolk wind data. The calculation of significant wave height was accomplished using the following formula (Equation 3-21 of the Corps' 1977 Shore Protection Manual):

$$\textbf{Significant Wave Height} = \mathbf{0.283*tanh(0.0125*gF/U^2)^{0.42}*U^2/g}$$

U = Wind Speed (miles/hour),
F = fetch (miles)

A graphical interpretation of this formula can be seen in Figure 3-15 of the Shore Protection Manual (Figure 1 of this document).

Once the significant wave heights for each of the wind speeds were found, a wave power index value for a specific location was calculated for a particular wind direction.

This index value is similar to the power index used by Dr. Robert Dolan and Dr. Robert Davis of the University of Virginia in their classification of extratropical storms or "nor'easters". The wave power index formula used in this thesis was:

$$\mathbf{WPI_x = O * W^2}$$

O = decimal value of % occurrence of winds from a particular direction
W = significant wave height (meters)
X = mid-range of wind speed (3 mph, 8 mph, 16 mph, 26 mph, 36 mph, or 46 mph) from a particular wind direction

Wave power from a particular direction was thus found by summing up the individual wave power values for each of the six wind speed mid-ranges. This process was repeated for the other seven wind directions. Total wave power for a specific location was then determined by taking the sum of the wave power indices for each of the eight wind directions. This value is a measure of the extent and strength of waves that strike a particular reach of shoreline. It is important to note that the value is only a derived estimate and provides no physical meaning. Therefore, it is best used as a comparison between sites. With that in mind, total wave power was calculated using the following formula:

$$\mathbf{WPI_T = WPI_S + WPI_{SE} + WPI_E + WPI_{NE} + WPI_N + WPI_{NW} + WPI_W + WPI_{sw}}$$

WPI = Wave Power Index
T = Total
S = South
SE = Southeast
E = East
NE = Northeast
N = North
NW = Northwest
W = West
SW = Southwest

In order to find the percent value for the wave power parameter in the model, it was first necessary to find a maximum value of wave power within the boundaries of the study area. The location with the largest wave power for a shoreline was determined to be located at Grandview Park in Hampton. Wave power for that location was calculated as 165. This number was used as the maximum wave power value for the model. Using this maximum value, the wave power values for each of the locations were found according to the following relationship:

$$\textbf{Wave Power Parameter (\%)} = [(\textbf{Wave Power})_P \,/\, (\textbf{Wave Power})_M]*100$$

P = wave power at a specific point
M = maximum wave power (165)

The next parameter, shoreline exposure, was determined in conjunction with the calculation of fetch distances for each shoreline location. Calculating the value for shoreline exposure was accomplished by counting the number of directions out of eight on the compass rose with a fetch greater than 0.5 kilometers. A minimum distance of 0.5 kilometers was used to ensure that small fetches, which result in minimal impact of wave energy on the shoreline, were not counted. Shorelines with at least five of the eight directions on the compass rose with fetches greater than 0.5 kilometers over water were characterized as having maximum shoreline exposure. Moderate shoreline exposure describes shorelines with three or four significant fetch directions falling over water. Finally, locations with less than three significant fetches were characterized as having minimal shoreline exposure. Such locations typically occur in small tidal creeks or in other shielded sections of shoreline.

For the nearshore bathymetry parameter, which is also a continuous variable, the distance to the 2-meter depth contour (in units of meters) was used as an indicator of the water depth and slope of the nearshore region. Determination of this parameter was also accomplished using an ARC/INFO AML. The AML utilized for the calculation of this parameter computed the shortest distance to the 2-meter depth contour over water. Arcs that fell over land were considered to have no 2-meter depth contour and, as a result, locations with such arcs were given a nearshore bathymetry instability value of 0%. For those locations in which a distance was found, the following equation was used to calculate the nearshore bathymetry value:

$$\textbf{Nearshore Bathymetry Parameter (\%)} = [(1 - (NB)_P/(NB)_M]*100$$

P = shortest distance to 2-meter contour for a specific point
M = maximum distance to 2-meter contour found in study area

The maximum distance to the 2-meter depth contour found along the western side of the Chesapeake Bay, VA was 3600 meters along the shoreline of Big Salt Marsh near Poquoson. This area is located off of Drum Island Flats and the Poquoson Flats, both of which are large shoals reaching out far into the Chesapeake Bay. Knowing the maximum value, the formula thus converts to:

$$\textbf{Nearshore Bathymetry Parameter (\%)} = [1 - (NB)_P/3600]*100$$

Such manipulation of the formula allows the weighting scheme to remain the same with high values of the nearshore bathymetry parameter correlating with greater instability. Thus, low values (relatively stable) occur for wide nearshore areas and larger values (relatively unstable) occur for narrow nearshore areas.

Data for the remaining three parameters (bank height, bank vegetation, and nearshore morphology) were determined through field observations. The necessary data were collected from shoal draft boats, which navigate along the shoreline, using hand-held Trimble Geo-Explorer Global Positioning Systems (GPS) receivers. These GPS units collect differential data with an accuracy of +/-1 decimeter after post-processing. Linear data was collected at a rate of 1 GPS point every five seconds, while point features were collected at a rate of 1 GPS point every second. The units were programmed with a "data dictionary" so that the necessary features could be logged from the boat. Therefore, each GPS position can be associated with a specific range of bank height, the extent of bank vegetation, and the presence of a marsh or beach along the shoreline.

Once the data was collected in the field, it was brought back to VIMS for processing. First, the data was transferred from the GPS unit to a computer at the Center for Coastal Resource Management's Comprehensive Coastal Inventory (CCI). After the data was transferred it was processed using the Trimble Pathfinder Office software package. The resulting files recorded the attributes observed on the shoreline, but their position recorded was relative to the course of the boat instead of the shoreline. Thus, the attribute data had to be translated back to the shoreline. This step was accomplished using the software ARC/INFO.

Weights for these three parameters were calculated as a percentage of a maximum condition that would result in the greatest likelihood of instability. Maximum conditions were given an instability weight of 100%, while minimum conditions were given an instability weight of 0%. Intermediate conditions were given an instability weight of 50% for this model. The ranges and classifications used for the model's bank height and bank vegetation parameters originated from the data collection efforts of the CCI's state-mandated Shoreline Inventory project. The classification system used for the nearshore morphology parameter was, however, a result of a review of the literature and field experience.

The following describes the maximum, minimum and intermediate conditions for these three parameters:

Bank Height

Maximum (100%):	0-5 feet
Intermediate (50%):	5-10 feet
Minimum (0%):	> 10 feet

Bank Vegetation

Maximum (100%):	Bare (0-25% of the bank is covered)
Intermediate (50%):	Partial (25-75% of the bank is covered)
Minimum (0%):	Total (>75% of the bank is covered)

Nearshore Morphology

Maximum (100%):	No Marsh, No Beach
Intermediate (50%):	Either a Marsh or a Beach
Minimum (0%):	Both a Marsh and a Beach

Once these parameters were determined and given a percentage weight of shoreline instability, a total percentage value of the level of shoreline instability was calculated for each location. A shoreline instability factor of 100% corresponds to the greatest likelihood of shoreline instability. Similarly, a shoreline instability factor of 0% corresponds to the least likelihood of shoreline instability (or rather, the greatest likelihood of shoreline stability). Instability factors between 0 and 100% correspond to a moderate likelihood for shoreline instability, depending on the proximity of the instability factor to either of the extreme values. The following equation describes the process for obtaining a final shoreline instability factor:

$$\mathbf{S = [(P1 + P2 + P3 + P4 + P5 + P6)]/6}$$

S = Shoreline Instability (%)
P1 = Wave Power parameter (out of 100%)
P2 = Nearshore Bathymetry parameter (out of 100%)
P3 = Nearshore Morphology parameter (out of 100%)
P4 = Bank Height parameter (out of 100%)
P5 = Bank Vegetation parameter (out of 100%)
P6 = Shoreline Exposure parameter (out of 100%)

This process of obtaining a final shoreline instability factor was applied to a select number of study areas along the western side of the Chesapeake Bay, VA. Six study areas were chosen for this thesis. At each of the six chosen study areas, locations were chosen in 0.5-kilometer increments from the beginning to the end of the study area.

Study Area Sites

Sites were chosen individually for specific characteristics in order to come up with a cumulative study area that represented a wide range of shoreline types. Since the model attempts to predict the instability of a shoreline based on six shoreline parameters, testing whether the model can consistently predict shoreline instability will therefore be enhanced through validating a larger amount of shoreline types. Figure 2 displays the geographic locations of these study area sites.

In Lancaster County (Figure 2a), shoreline from Mosquito Point on the Rappahannock River around Fleets Island to North Point was analyzed. Shoreline within this section of the county is adjacent to the mainstem of the Chesapeake Bay and thus experiences a higher wave energy climate. The Rappahannock Spit tends to dampen much of the wave energy coming off of the Bay, however. Bank heights are mostly less than ten feet in this area and nearshore depths tend to be less than six feet. Much of this area has been developed and contains many private residences, but sections of forest can also be found.

Another site that was analyzed was the area between Wilton Point and Stove Point along the Piankatank River in Middlesex County (Figure 2b). This section of shoreline is shielded from the mainstem of the Chesapeake Bay by the land formation at Stove Point and, as a result, short fetches are common. A majority of this section of shoreline lies in an embayment, but the shoreline slope is steep and water depths drop to over 20 feet quickly in the nearshore region. In addition, the bank heights of these shorelines are very high (>15 feet) in many sections and show evidence of much bank erosion. Finally, a large amount of shoreline is developed within this study area.

Another section chosen as a study area was Gwynn Island in Mathews County (Figure 2c). The eastern side of the island is exposed to the mainstem of the Chesapeake Bay and therefore experiences a high wave energy environment. This side of Gwynn Island also has a high percentage of sandy beaches that help protect the shoreline. Bank heights on Gwynn Island are typically low and the nearshore region slopes gently toward the deeper water of the Chesapeake Bay due to a large shoal. Thus, even with the high wind-wave environment and long fetches that the island experiences, the shoreline avoids devastating erosion by the presence of this shoal. The shoreline of Gwynn Island has, however, experienced continual erosion problems over the years.

For Gloucester County (Figure 2d) the section of shoreline that was used in this thesis was part of the Ware River, a tributary of Mobjack Bay. Even though the East, North, and Severn Rivers of Mobjack Bay are similar in many ways, the Ware River was chosen because it has a large variety of shoreline types. The part of the Ware River chosen for the model was from Ware Neck Point at the mouth of the Ware River to the mouth of Wilson Creek, one of its tidal creeks. Much of the shoreline is developed in this study area, but forested and scrub-shrub areas can also be found. Bank heights vary from less than five to up to ten feet, but nearshore areas are typically shallow and contain a lot of marshes. Fetches are typically small in this area except in a few sections that have significant fetches stretching out into the Chesapeake Bay.

A small portion of shoreline in the City of Poquoson (Figure 2e) was also chosen as a study area. This study area begins at the city line in Lambs Creek and ends at Hunts Point along the Poquoson River. Shoreline in this region is low-lying and marshy yet most of it has been developed. Bank heights tend to be mainly less than five feet, while nearshore regions are shallow. Also, fetches are short in this study area since the shorelines are sheltered from the long fetches of the Chesapeake Bay. Thus, the wave climate is relatively weak in comparison to some of the more exposed study areas used for this analysis.

The last section of shoreline chosen as a study area for this thesis was along the Rappahannock River in Essex County (Figure 2f). The shoreline that was analyzed lies between Lowerys Point and Bowlers Wharf. This stretch of shoreline is fairly straight and far from the mainstem of the Chesapeake Bay. Thus, fetches tend mostly to be short and wave activity not very strong. Bank heights in this region are mixed in that there are some high cliffs as well as some low-lying shorelines, while nearshore water is very shallow due to extensive tidal flats lying along the edge of the Rappahannock River. Much of the shoreline within this study area has been developed.

Shoreline Rate-of-Change

Once values for the six parameters were determined for the locations in these six study areas, an historical shoreline rate-of-change value was calculated for each location. This rate serves as the dependent variable for the model and is compared to the calculated instability factors to determine the model's accuracy. Calculation of historical rates-of-change was accomplished using 1994 Digital Orthophoto Quarter Quad (DOQQ) images as well as aerial photos taken in 1937. Scale variations associated with aerial photos include: 1) radial distortion away from the center of the photograph; 2) camera tilt and pitch distortion; 3) altitude changes in aircraft along a flight line; and 4) relief or elevation distortion. It has been found that image rectification, or the process of assigning map coordinates to physical locations on the earth, removes some of the errors due to scale variations and tilt. Associated errors are usually on the order of only a few meters when such variations are removed through geo-rectification (Nelson, 1995).

For the 1994 DOQQ images, geo-rectification had previously been done of the photos and thus no further processing was needed. The 1937 aerial photos, however, had to be geo-rectified. This was done through Imagine, Earth Resources Data Analysis System's (ERDAS) raster-based computer imaging software package used for area classification. The first step in this process was to scan the photo into the computer using HP Precision Scan Pro at an output resolution of 300 dots per square inch (dps) and with an output type of true color. The scanned image was saved as a jpeg file. Then, using Imagine, the aerial image was processed through geo-rectification. The jpeg image was imported into Imagine and converted to an image (.img) file before such correction could begin. The geometric model used for processing was polynomial of order one, while the projection type used was Universal Trans Mercator (UTM). The spheriod, which defines a geodetic datum or a smooth mathematical surface that closely fits the mean sea-level surface throughout the area of interest, used in the processing was GRS 1980 and the datum was the grid based NAD83. This datum includes the Continental United States. Finally, the UTM zone used for processing was Zone 18 North.

Each of the 1937 photos was geometrically corrected by linking the digitally scanned ERDAS images to corresponding stable points (e.g. road intersections, buildings, private residences) on the 1994 DOQQs. A total of six points found in each of the photos were used to geo-rectify the image. Only RMS errors of less than 2 meters were accepted. After geo-rectifying the 1937 aerial image, "past" and "present" shoreline locations were then digitized in ARC/INFO by tracing the apparent HWL, or the landward extent of the last high tide, observed in each image. Errors associated with digitizing on the screen have been found to be +/- 6.0 meters, while the errors associated with delineating the HWL have been found to be +/- 3.0 meters (Nelson, 1995).

An overlay of both the 1937 and 1994 shoreline position was used to determine the relative rate-of-change of a specific point on the shoreline. To calculate the rate of change, the distance perpendicular from each of the model's locations on the 1994 shoreline to the 1937 line first had to be determined. Once this distance was found, it was then divided by the number of years between the two photos (1994-1937=57 years) to obtain the rate of shoreline change. If shoreline position had changed significantly such that a perpendicular line from the 1994 shoreline would not intersect the 1937 shoreline, an alternative method of finding the distance between shorelines was used. In this case, the shortest distance from the location on the 1994 shoreline to the 1937 shoreline was determined and divided by 57 to obtain the rate of shoreline change. This alternative method typically had to be utilized in tidal creeks and other highly fluctuating areas (i.e. inlet mouths, outside of meanders in a river bend).

Due to the associated errors involved with digitizing the "past" and "present" shoreline locations, the relative certainty of the rates of shoreline change for a particular location is small. Delineating the HWL for each shoreline position (i.e. "past" and "present") involved an error of at least +/-9.0 meters [(+/-6.0) + (+/-3.0)]. As a result, there is a cumulative error associated with the geo-rectification process of at least +/-18.0 meters for both images. For changes in shoreline position between the "past" and "present" images that are less than 18 meters, there is a lower confidence in reporting the rates of shoreline change than for changes in position greater than 18 meters.

At the end of this entire process, for locations 0.5-kilometers apart in each of the six study areas, data was found or calculated for the six parameters and used to determine an instability factor. The percent instability factor at each location describes the likelihood of shoreline instability, with higher factors indicating greater probabilities for instability. Also, for each location, a rate-of-change for shoreline position between 1937 and 1994 was found. Only locations where data were missing, or areas where significant dredging or filling of the land had been observed, were removed. The next step in the process was to calibrate the model.

Model Calibration Process

The model was calibrated using two statistical approaches: 1) Principal Components Analysis (PCA), and 2) multiple regression. Both types of analyses were performed using the statistical computer software SAS. The purpose of the first type of analysis, PCA, is to derive a small number of linear combinations (principal components or PCs) of a set of variables that retain as much of the information in the original variables as possible. PCA helps uncover any linear dependencies among the variables used in the analysis and allows one to reduce the number of variables.

The first step in analyzing the PCA results was to look at the correlation matrix to see if any of the variables correlated highly with each other. Pairs of factors with correlation factors greater than 0.5 (50%) were considered important. Next, it was noted how much of the overall variance each of the six calculated PCs explained. Using the Kaiser Criterion, only factors with eigenvalues (lengths of the orthogonal ellipse axes) greater than 1 were retained. This rule was followed so that only factors that extract at least as much as the equivalent of one variable would be included. The next step was to examine the eigenvectors of each of the variables for the PCs. Eigenvectors describe the amount that each variable contributes to the overall principal component, and are listed as a decimal between 0 and 1. Higher eigenvector values for a variable signifies that the variable explains a greater percentage of the principal component. Parameters that have eigenvector values which explain a large percentage (>50%) of a particular principal component were considered significant. The results from the PCA were then compared to the results obtained from the multiple regression analysis.

Multiple regression determines the correlation between each of the independent variables and the dependent variable (shoreline rate-of-change) in the model. For the purposes of this type of analysis, the rates of shoreline change were kept as absolute values. Thus, the dependent variable used in this analysis did not reflect erosion or accretion, but rather a change of shoreline position over time. For the multiple regression analysis, a Pearson correlation coefficient (R^2) was calculated to show the correlation between the predicted values of shoreline rate-of-change based on the independent variables and the observed values of the dependent variable. R^2 is defined as the proportion of the sum of squares equal to the ratio of sum of squares predicted over the total sum of squares (predicted values plus error values). This coefficient serves as a means to measure how well the model is working. Higher correlation coefficients would translate into a better fitting model. To test whether an R^2 was significantly different from the hypothesized value of zero (the null hypothesis), an F value was calculated using the following formula:

$$\text{-------------------} \qquad \text{where N is the number of observations,}$$

$$(1 - R^2) / (N\text{-}k\text{-}1) \qquad \text{and k is the number of predictor variables}$$

$$F\ (k, N\text{-}k\text{-}1) = \frac{}{(1 - R^2) / (N\text{-}k\text{-}1)}$$

where N is the number of observations, and k is the number of predictor variables

The F statistic is thus the ratio of the explained variation to the unexplained variation divided by the respective degrees of freedom. The significance test used calculates the probability of obtaining an R^2 as different from the null hypothesis (given the null hypothesis is correct) than the R^2 obtained in the sample. Low probabilities of less than 0.05 indicate that the difference between the hypothesized value and the calculated R^2 and are said to be "statistically significant" at the 0.05 significance level. Large values of F provide better evidence for rejection of the null hypothesis.

In addition to testing R^2 for significance, each of the six individual regression coefficients (or parameter estimates) was tested for significance. This testing was accomplished by dividing the regression coefficient by the standard error of the regression coefficient in order to find the T value. Such a calculation is performed using the following formula:

$$T\ (N\text{-}k\text{-}1) = \frac{b}{s_b}$$

where b is the regression coefficient, s_b is the standard error of the coefficient, N is the number of observations, and k is number of predictor variables

This T value was the value that was tested for significance against the null hypothesis that the parameter estimate is zero.

RESULTS AND DISCUSSION

The entire data set for the model was comprised of 303 locations. These locations were divided up between each of the six model calibration study areas. The Lancaster County study area contained 74 locations, while the Middlesex County study area had 72 locations. Two of the medium-sized study areas, Mathews County and Gloucester County, contributed 54 and 55 locations, respectively. Finally, the two small study areas were the City of Poquoson and Essex County. The City of Poquoson study area was comprised of 24 locations, and Essex County added another 24 more.

Data for these 303 locations were used in a PCA. The correlation matrix from this analysis revealed a high correlation between wave power and shoreline exposure (Table 3). These two parameters had a correlation of 0.5876. Shoreline exposure was also highly correlated with nearshore bathymetry (0.6047). None of the other parameters in the model were highly correlated, however. The eigenvalues, or the variances extracted by the principal components, showed high values for the first two principal components only. Principal Component 1 had an eigenvalue of 2.13, while Principal Component 2 had an eigenvalue of 1.54. Together these two principal components explained 61.1% of the variance. The other principal components had eigenvalues of less than one. Thus, these principal components were not considered to be significant.

The first principal component contained high eigenvectors, or component loadings, for wave power, nearshore bathymetry and shoreline exposure. The eigenvectors for wave power and shoreline exposure were 0.54 and 0.59, respectively, while the eigenvector for nearshore bathymetry was 0.52. It appeared, therefore, that these three parameters explained the bulk of the variance. The other parameters were not as significant in the first principal component. These parameters were found to be significant in the second principal component, however. In this component, bank height had a high negative eigenvector (-0.64), while bank cover and nearshore morphology had relatively high positive eigenvectors (0.54 and 0.47, respectively). The results of the PCA pertaining to the eigenvectors for the six parameters in the first two principal components are listed in Table 4.

It is interesting to note that in the second principal component the first three parameters, which are indicative of offshore physical processes, were found to be insignificant while the parameters involving bank characteristics were significant. The opposite occurred for the first principal component (i.e. parameters involving offshore processes had high component loadings while parameters involving bank characteristics had low component loadings). Thus, the PCA distinctly divided the parameters into two types of factors. This means that the bank characteristics vary independently from offshore processes, and both influence the hypothesized six-parameter shoreline instability rating determined in this model.

A multiple regression analysis of the original 303-location data set was then performed. The analysis resulted in an R^2 of 0.2910, indicating a rather small correlation between the six independent variables and the dependent variable. This Pearson correlation coefficient was found to be significant at the 0.01 significance level. In addition, wave power was the only one of the six parameters with a regression coefficient significant at the 0.05 level. This significance, along with explaining a large percentage of the variance in the first PC, indicates that wave power is the one factor most likely driving the model. Shoreline exposure and nearshore bathymetry, despite being significant in the first principal component of the PCA, were not significant in the multiple regression analysis. As for the three parameters describing bank characteristics that were found to be significant in the second principal component, none were found to be statistically significant at the 0.05 significance level in the multiple regression analysis. Thus, these parameters were not considered important for the model. Table 5 lists the results obtained in the multiple regression analysis for the 303-location original data set.

Figure 3 shows the measured rates of shoreline change for locations in the original data set based on predicted shoreline instability factors. The low correlation between the measured shoreline rate-of-change and predicted shoreline instability factor can be seen in that small rates of shoreline change exist, as expected, for many of the low instability factors, but not as expected for some of the large instability factors. For the model to be accurate, the larger measured rates of shoreline change should correlate well with larger shoreline instability factors while smaller measured rates of shoreline change should correlate well with smaller shoreline instability factors.

Even though wave power was found to be significant in the model for the original 303-location data set, the R^2 value was still too low, indicating that the model did not accurately predict shoreline instability for all of the locations. The next step was therefore to test the model with various subsets of the original data set. Such subsets would be based on specific ranges of each of the three offshore process parameters since the first principal component was the only one with a parameter found to be significant. These subsets were analyzed using multiple regression analyses. Higher R^2 values would indicate that the model more accurately predicted shoreline instability.

The first subset analyzed was comprised only of locations with high wave power (>10). This subset was chosen because wave power was found to be significant in both the PCA and multiple regression analyses of the original data set. Seventy-four locations remained after removing the low wave power locations from the original data set. The multiple regression analysis for this data set revealed a Pearson regression coefficient almost as low as the one for the original data set. The R^2 for this data set was 0.2896 and it was found to be significant at the 0.01 significance level. This low R^2, however, indicated that removing low wave power locations from the original data set did not increase the overall reliability of the model.

Instead of removing only low wave power locations from the original data set, locations with low shoreline exposure parameters were removed from the original data set. Such locations are shielded from wave attack and typically can be found in tidal creeks or far from the mouth of the Chesapeake Bay. It was thought that removing relatively shielded shorelines would increase the wave-driven model's accuracy since exposed shorelines tend to be the ones mainly influenced by wave activity. The removal of low exposure sites (equal to 0) retained 119 of the original 303 locations. A multiple regression analysis of this data set revealed an R^2 value of 0.3740 that was significant at the 0.01 significance level. This R^2 value is higher than the one previously found for the data set of high wave power locations, but it still indicates that the model did not improve its accuracy significantly by removing low exposure sites.

The next step was to test whether the presence of a 2-meter depth contour offshore was the most influential factor. The presence of this depth contour means that deeper water exists offshore and that waves approaching the shore will be larger than along shorelines with relatively shallow water offshore. Removing locations without a 2-meter depth contour offshore (equal to 0) retained a total of 178 locations out of the original 303 locations. The regression analysis of this data set revealed a lower R^2 value than the one for the data set with low exposure sites removed, but higher than the one with low wave power locations removed. The Pearson correlation coefficient was 0.3423 and it was found to be statistically significant at the 0.01 significance level. These results indicate that the model also does not work well when locations without a 2-meter depth contour offshore are removed from the original data set.

Since individually looking at data sets based on a specific subset of one parameter did not appear to drastically increase the model's reliability, data sets were created using combinations of these three parameters. The first one of these combinations was the data set with locations having high wave power and moderate to high exposure. This data set was comprised of 122 locations out of the 303 original locations. A regression analysis of this data set once again resulted in a low R^2 value. The Pearson correlation coefficient for this analysis was 0.3273 and it was found to be statistically significant at the 0.01 significance level.

The next combination was high wave power locations with a 2-meter depth contour offshore (nearshore bathymetry > 0). As it turned out, there was only one location from the data set of only high wave power locations that had a nearshore bathymetry value of zero. Thus, this data set of 73 locations was only one location less than the one previously tested containing 74 locations. The regression analysis revealed an R^2 value of 0.3307 for this data set. This coefficient was found to be statistically significant at the 0.01 significance level. Similar to the other analyses, the R^2 value was still too low to make any definite conclusions about which data set fit the model the best.

For the last combination of these three parameters (moderate to high exposure locations with a 2-meter depth contour offshore), there were 116 locations out of the original 303 locations. The regression analysis for this data set returned the highest R^2 value thus far. The Pearson correlation coefficient for this data set was 0.3905 and it, too, was found to be statistically significant at the 0.01 significance level. In this analysis, all three offshore process parameters (wave power, nearshore bathymetry, and shoreline exposure) were found to be statistically significant at the 0.05 significance level.

Even though this combination appeared to have the highest R^2 value, one more analysis using the combination of all three parameters was performed to see if the R^2 would increase. This final data set contained sites with a 2-meter depth contour having moderate to high exposure and high wave power. Such a combination ensured that only locations influenced by wind-wave energy were analyzed. The regression analysis for this data set of 70 locations did, in fact, result in the greatest R^2 (0.3943) found among all of the combinations. The R^2 value was found to be statistically significant at the 0.01 significance level. Also, all three offshore process parameters were once again all found to be significant at the 0.05 significance level. Thus, the model appeared to fit this data set the best. Table 6 gives the multiple regression analysis results for each of the subsets. Table 7 shows the significance test results for the individual regression coefficients of the final 70-location data set.

The final data set containing locations with a 2-meter depth contour and having moderate to high exposure as well as high wave power was further analyzed to determine how well the calculated instability factor predicted shoreline rate-of-change. A linear regression analysis was performed for this purpose. This analysis resulted in an R^2 value of only 0.0679 and a small F value of 8.378, which means low evidence for rejecting the null hypothesis. The results indicate that even though the model appeared to fit this data set the best, the calculated instability factor was by far not a good predictor of shoreline rate-of-change. Figure 4 illustrates the improvement of the model in predicting shoreline instability for the 70-location final data set over the original 303-location data set, but shows that the model still is not very precise.

Since bank height, bank cover, and nearshore morphology were not found to be significant in any of the previous analyses, these parameters were dropped from the final data set. New instability factors were re-calculated by taking the average of the three offshore process parameters at each location in the data set, and then compared to the rates of shoreline change. A new linear regression analysis was performed for the three-parameter data set, resulting in a much higher F value of 51.658 and a higher R^2 value of 0.3118. This higher F value provides greater confidence in rejecting the null hypothesis. Even though the R^2 correlation coefficient is much larger in this three-parameter model than the one found for the previous six-parameter model, this value is still not high enough to conclude that the model accurately predicts shoreline instability. Figure 5 shows that by reducing the model from six parameters to three for this 70-location data set, there is a much better fit between instability factors and rates of shoreline change.

Changing the weights applied to each of the three parameters was then attempted in order to see if the model could better predict rates of shoreline change. Since wave power was found to be the only significant parameter occurring throughout the data analyses, this parameter was assigned a greater weight than nearshore bathymetry and shoreline exposure. Wave power was arbitrarily given a weight twice as much than nearshore bathymetry and shoreline exposure in the new calculation of the instability factor. The equation used to calculate the new instability factor was transformed from the original equal weighting one to the following equation:

$$S = [(0.5)WP + (0.25)NB + (0.25)SE)]$$

S = Shoreline Instability (%)
WP = Wave Power (%)
NB = Nearshore Bathymetry (%)
SE = Shoreline Exposure (%)

The regression analysis of instability factor versus shoreline rate-of-change using the adjusted parameter weights yielded a higher R^2 (0.3626) than the regression analysis of instability factor versus shoreline rate-of-change using the non-adjusted parameter weights (0.3118). In addition, the F value increased from the previous 51.658 to 64.838, which is the highest value found thus far. These results indicate that adjusting the parameter weights actually did improve the ability of the model to predict shoreline rate-of-change, albeit only slightly. Table 8 gives the linear regression results from the analysis of instability factor versus shoreline rate-of-change for the final data set (6-parameter model, 3-parameter model, and 3-parameter model with adjusted weights). Figure 6, which shows the measured rates of shoreline change for the 70 locations based on predicted shoreline instability, reveals that the 3-parameter model with adjusted weights provides a slightly better fit of the data set than the 3-parameter model without adjusted weights.

While dropping three of the parameters from the model appeared to make the model more accurate at predicting shoreline rate-of-change, the overall correlation between the three independent variables and the dependent variable was still not high enough to make the model useable in real-world situations. It was thought that much of the model's inconsistency resulted from the effects of managing the shoreline (i.e. erosion control devices). Such devices block or deflect incoming wave energy that reaches the shore, thereby making potentially unstable sites less unstable. To test this theory, locations with erosion control devices in place were removed from the 70-location data set containing only sites with moderate to high exposure, high wave power and a 2-meter depth contour offshore. Twenty-six locations remained after removal of such locations. The remaining locations were distributed throughout the study area except for in the mainly shielded City of Poquoson site.

A linear regression analysis of the instability factor versus shoreline rate-of-change for the 3-parameter model with adjusted weights was performed and resulted in a much higher R^2. The R^2 for this data set was 0.6914, but the F value was only 53.776. This lower F value was attributed to the smaller sample size, meaning that a greater sample size would be needed to accurately determine if this R^2 value was precise. Despite this lower confidence, it was presumed that removing all of the managed shorelines did increase the model's accuracy. Figure 7 is a plot of shoreline rate-of-change versus instability factor for the 3-parameter model with adjusted weights for the 26 locations in the final data set without shoreline armoring. In this figure, it can be seen that most of the locations with low instability factors have small rates of shoreline change, while most of the locations with high instability factors have larger rates of shoreline change.

The final piece of the puzzle was to determine if the level of model accuracy further increased by removing locations that have adjacent (<0.5 km) erosion control devices. Adjacent erosion control devices also have the potential to affect the stability of a downstream shoreline. The placement of a bulkhead along a shoreline typically directs the incoming wave energy off of the wall towards downstream areas. This deflection of energy usually results in more unstable conditions along the downstream shoreline. Such an energy transfer is also seen for locations with riprap installed, but not to the same extent since riprap absorbs some of the incoming energy. For groins and jetties, their placement affects areas both upstream and downstream. Areas downstream from a groin or jetty will experience greater instability due to less sediment being shifted along the shore. Upstream areas will experience similar instability, although this will be in the form of accretion due to sediment getting trapped by the structure instead of being moved along the shore.

The data set for this analysis was comprised of only 16 out of the original 303 locations. Eight of the locations were in the Lancaster County study area, five were located in Essex County, two were located in Gloucester County and one was located in Middlesex County. Despite the small size of the data set, it represented the only locations that were "pristine" or not influenced by erosion control devices within the study area that also fit the criteria of moderate to high exposure, high wave power, and the presence of a 2-meter depth contour offshore. The regression analysis of this 16-location data set resulted in the highest R^2 found. An R^2 of 0.7714 was found for this data set, but the F value decreased once again to 47.236. Thus, even though the R^2 value was increasing, the confidence of reporting this value was decreasing. Once again, this could be due to the lower size of the data set of locations with armored and adjacent armoring locations removed.

A plot of the instability factors versus shoreline rate-of-change (Figure 8) for this data set displays the best-fit line for the model, indicating that the rate of shoreline change increases with increasing instability factor values. Only a few locations in this data set did not follow this pattern. Results from the linear regression analyses of instability factor versus shoreline rate-of-change for the final model data set without armored locations and without armored as well as adjacent armored locations can be seen in Table 9.

MODEL VALIDATION

After the model was calibrated, four small sections of shoreline were used to validate the 3-parameter model with adjusted weights (see Figure 2 for geographical locations). The first section was in Mathews County near Winter Harbor (Figure 2g). It lies along the mainstem of the Chesapeake Bay. This stretch of shoreline has large fetches, moderate offshore depths, extensive marshes and little development. The second section was in Lancaster County along the southern-facing shoreline of Belle Isle State Park along the Rappahannock River (Figure 2h). Fetches are much smaller along this stretch of shoreline and nearshore depths are smaller as well due to the extensive shoals flanking the river.

The third section of shoreline used to validate the model was from Mallorys Point to Mount Landing Creek in Essex County along the Rappahannock River (Figure 2i). This section of shoreline is exposed to moderate fetches, but is far from the mouth of the Chesapeake Bay. Nearshore depths are also small along this shoreline. The final area used to validate the model was in Middlesex County from the mouth of Weeks Creek to Long Point (Figure 2j). This section of shoreline faces to the north along the Rappahannock River and is close to the mouth of the Chesapeake Bay, thus it experiences moderately high wave energy.

Validation was accomplished through running the fetch and nearshore bathymetry AMLs to obtain the wave power and nearshore bathymetry parameter values. The shoreline exposure parameter was determined using the results from the fetch AML. After finding these three parameter values for each of the locations in the four model validation study areas, instability factors were calculated. The calculation of the instability factors was based on the adjusted parameter weights previously determined for these three parameters. The last step was to calculate a shoreline rate-of-change with the assistance of the 1994 and 1937 aerial images. The 1937 aerial photos had to be geo-rectified first before such calculations could be made. A linear regression analysis was used to measure the degree to which the independent variables correlate with the dependent variable, and thus how well the calibrated model predicted the shorelines in the validation study areas.

The data set used to validate the model was comprised of locations meeting the same conditions as locations in the final data set (moderate to high exposure, high wave power, the presence of a 2-meter depth contour offshore, no shoreline armoring, and no adjacent shoreline armoring). Within the four study areas used to validate the model, 22 locations were analyzed. The low number of model validation locations was due to the relative difficulty in finding stretches of unmanaged shoreline that met these criteria. For the model validation data set, the regression analysis of instability factor versus shoreline rate-of-change revealed an R^2 value of 0.6630. This value, which is less than the R^2 value of 0.7714 determined for the final data set, was found to be statistically significant at the 0.01 significance level. Despite the lower R^2 value, however, this result indicates a moderately good fit of the validation data set to the calibrated model.

A plot of instability factors against rates of shoreline change (Figure 9) for the model validation data set using the 3-parameter model with adjusted weights shows that the calibrated model moderately predicts shoreline instability. This can be seen in that most of the smaller instability factors have small rates of shoreline change, whereas most of the higher instability factors have more substantial rates of shoreline change. A few of the higher instability factor locations, however, do have negligible rates of shoreline change. This result points to the fact that this model does not always accurately predict shoreline instability based on the three parameters. Other factors outside of the scope of this model are involved, therefore, in determining the relative instability of the shoreline.

CONCLUSIONS AND FUTURE WORK

Based on the results of the shoreline instability model validation, it is concluded that the 3-parameter model with adjusted weights moderately predicts the level of shoreline instability based on the three significant offshore physical process parameters. The R^2 value determined in the model validation analysis indicates that there is some correlation between the calculated shoreline instability factor and the measured rates of shoreline change. High instability factors for a given shoreline location tended to have larger rates of shoreline change (either erosion or accretion), while low instability factors have more minimal rates of shoreline change.

The PCA revealed that two separate factors seem to be affecting the hypothesized six-component shoreline instability rating. Results indicated that offshore processes (i.e. wave power, nearshore bathymetry, and shoreline exposure) related to wind-wave energy and bank characteristics (i.e. bank height, bank cover, nearshore morphology), which affect the extent to which incoming wave energy impinges on the shoreline, are important. These two factors appear to be independently influencing the shoreline instability rating at locations within the study area.

These conclusions were determined to only be valid under a precise set of conditions. It was found that the model could only be accurately used for shorelines that have a 2-meter depth contour offshore, have high wave power and that have at least a moderate exposure to significant wave energy. Thus, it was determined that the model could not be applied to shielded sections of shoreline, especially those along tidal creek shorelines as well as those in the upper reaches of the Chesapeake Bay's tributaries, where wave energy is not significant. This limitation, in effect, rules out many stretches of shoreline along the western side of the Chesapeake Bay. In addition, the model only applies to unmanaged shorelines with no shoreline erosion control devices protecting the shoreline or in the immediate vicinity. The presence of these structures skews the results of the model by making previously unstable locations less unstable.

Since the model markedly improved in accuracy once shorelines with armoring or adjacent armoring were factored out, future analyses could concentrate on determining the importance of these two additional variables on predicting shoreline instability. A first step in this process was carried out here with a PCA of the original 303-location data set with the shoreline armoring and adjacent armoring parameters added. The results of this analysis (see Table 10) revealed three principal components to be significant as compared to two in the analysis of the six-parameter data set. Similar to the results from this previous analysis, the first PC had high eigenvectors for the three parameters related to offshore physical processes and low eigenvectors for the other five parameters. The second PC had high eigenvectors for the three parameters related to bank characteristics and low eigenvectors for the remaining parameters. In this analysis of the eight-parameter data set, however, the third PC had high eigenvectors for shoreline armoring and adjacent armoring, and low eigenvectors for the remaining parameters.

This analysis suggests that instead of just two independent factors influencing shoreline type and, potentially, shoreline instability, there is a third external factor largely independent of bank characteristics and offshore physical processes. Additional analyses on the relationship between shoreline armoring and adjacent armoring on shoreline rate-of-change should be performed in order to determine the importance of these factors in predicting shoreline instability.

It was thought in addition to shoreline armoring, other factors play an important role in determining shoreline instability along tidal shorelines of the western side of the Chesapeake Bay, VA. Storm strength and duration are hypothesized to be crucial factors in determining shoreline instability along exposed shorelines. Even though wave power was found to be a good measure of predicting the relative extent of shoreline instability along such shorelines, further incorporating the effects of storms into the analysis would greatly enhance this prediction at a given location. The reason is that erosion tends to be episodic in nature such that shoreline rate-of-change often is influenced more by specific events than longer trends.

For the more shielded shorelines, especially those without a 2-meter depth contour offshore, a different set of factors is thought to affect the stability of a shoreline. Since wave conditions are not as prominent in these areas, tidal forces are thought to be influential in shaping these shorelines. In addition to tidal currents, boat wakes are thought to cause much of the observable erosion along shielded shorelines of heavily traveled waterways. Finally, the level of storm surge is thought to be one of the deciding factors in shoreline instability. Along shorelines with the potential for high storm surge levels, higher levels of instability are expected to occur. Additional research is needed to be able to accurately predict the instability for these types of shorelines.

While the model appeared to moderately predict shoreline instability, further refinement of the parameter weights is needed to improve the outcome of the model. It must be noted that the adjusted parameter weights were only a best professional judgment and did not constitute a precise measure of actual correlation with the dependent variable. With the help of more advanced statistical techniques, further alteration of the wave power, nearshore bathymetry, and shoreline exposure parameter weights could potentially improve the ability of the model to predict shoreline instability. Another aspect needed to fully validate the model is a larger number of shoreline locations that meet the designated criteria. A larger data set would help determine the accuracy of the conclusions obtained from this analysis.

This Masters of Science thesis served as just the beginning of analyzing the types of shoreline conditions along the western side of the Chesapeake Bay, VA and as a first step in deriving a method for predicting the instability of these shorelines. The state-mandated shoreline inventory project undertaken by VIMS' Coastal Inventory has amassed a large and growing data set of shoreline conditions around the state. This thesis served as the first attempt to analyze this data set. With much to come in the way of analyzing this growing data set, the goal of achieving standards for managing tidal estuarine shorelines around the state can be reached.

TABLE 1.
List of Factors Affecting Shoreline Stability

fetch
land use
bank height
sea level rise
bank vegetation
upland sediment type
waves/longshore currents
erosion control structures
natural buffers (e.g. marsh, beach)
shoreline structures (e.g. docks, boathouses)
shoreline configuration (or exposure)
nearshore water depth
average wind direction
average wind speed
storm frequency
storm strength
tidal currents
boat wakes

TABLE 2.
Summary of Wind Conditions at Norfolk International Airport from 1960 to 1990

		WIND DIRECTION								
Wind Speed (mph)	**Mid Range (mph)**	**South**	**South west**	**West**	**North west**	**North**	**North east**	**East**	**South east**	**Total**
< 5	3	5497* 2.12+	3316 1.28	2156 0.83	1221 0.47	35748 13.78	2050 0.79	3611 1.39	2995 1.15	56594 21.81
5-11	8	21083 8.13	15229 5.87	9260 3.57	6432 2.48	11019 4.25	13139 5.06	9957 3.84	9195 3.54	95314 36.74
11-21	16	14790 5.70	17834 6.87	10966 4.23	8404 3.24	21816 8.41	16736 6.45	5720 2.20	4306 1.66	100572 38.77
21-31	26	594 0.23	994 0.38	896 0.35	751 0.29	1941 0.75	1103 0.43	148 0.06	60 0.02	6487 2.5
31-41	36	25 0.01	73 0.03	46 0.02	25 0.01	162 0.06	101 0.04	10 0.00	8 0.00	450 0.17
41-51	46	0 0.00	0 0.00	0 0.00	1 0.00	4 0.00	4 0.00	1 0.00	0 0.00	10 0.00
Total		41989 16.19	37446 14.43	23324 8.99	16834 6.49	70690 27.25	33133 12.77	19447 7.50	16564 6.38	259427 100.00

*Number of occurrences   +Percent

TABLE 3.
Correlation Matrix for PCA of 303-Location Original Data Set (6 Parameters)

	WP	BATH	EXP	MORPH	HEIGHT	COVER
WP	1.00	0.37	0.59	-0.20	0.14	-0.01
BATH	0.37	1.00	0.60	-0.13	-0.05	0.03
EXP	0.59	0.60	1.00	-0.13	-0.02	0.03
MORPH	-0.20	-0.13	-0.13	1.00	-0.35	0.17
HEIGHT	0.14	-0.05	-0.02	-0.35	1.00	-0.32
COVER	-0.01	0.03	0.03	0.17	-0.32	1.00

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TABLE 4.
Eigenvectors for PCA of 303-Location Original Data Set (6 Parameters)

	Principal Component 1	Principal Component 2
Wave Power	0.540818	0.021856
Nearshore Bathymetry	0.517561	0.213636
Shoreline Exposure	0.587754	0.199799
Nearshore Morphology	-0.272323	0.468123
Bank Height	0.131035	-0.638576
Bank Cover	-0.053496	0.535768

TABLE 5.
Multiple Regression Analysis Results for 303-Location Original Data Set (6 Parameters)

	T Value	Prob > |T|
Wave Power	8.972	0.0001
Nearshore Bathymetry	-1.252	0.2115
Shoreline Exposure	0.245	0.8065
Nearshore Morphology	1.188	0.2358
Bank Height	0.842	0.4007
Bank Cover	0.428	0.6691

TABLE 6.
Results from Multiple Regression Analyses of Various
Subsets of 303-Location Original Data Set (6 Parameters)

	N	R^2	F Value	Prob > F
High WP	74	0.2896	4.621	0.0005
Med-High Exp	119	0.3740	11.250	0.0001
Bath>0	178	0.3423	14.922	0.0001
High WP/Med-High Exp	122	0.3273	9.406	0.0001
High WP/Bath>0	73	0.3307	5.518	0.0001
Med-High Exp/Bath>0	116	0.3905	11.748	0.0001
High WP/Med-High Exp/Bath>0	70	0.3968	7.018	0.0001

TABLE 7.
Results from Multiple Regression Analysis for Final Data Set of 70 Locations With a 2-meter Contour, Moderate to High Exposure, and High Wave Power

	T Value	Prob > |T|
Wave Power	3.014	0.0037
Nearshore Bathymetry	-2.875	0.0055
Shoreline Exposure	2.210	0.0307
Nearshore Morphology	-0.355	0.7238
Bank Height	0.154	0.8780
Bank Cover	0.653	0.5159

TABLE 8.
Results from Linear Regression Analyses of Instability Factor
Versus Shoreline Rate-of-Change for 70-Location Final Data Set
(6-Parameter Model, 3-Parameter Model, 3-Parameter Model with Adjusted Weights)

	R^2	F Value	Prob > F
6-Parameter Model	0.0679	8.378	0.0045
3-Parameter Model	0.3118	51.658	0.0001
3-Parameter Model with Adjusted Weights	0.3626	64.838	0.0001

TABLE 9.
Results from Linear Regression Analyses of Instability Factor Versus Shoreline Rate-of-Change for 3-Parameter Model with Adjusted Weights (Without Armored Locations, Without Armored and Adjacent Armored Locations)

	N	R^2	F Value	Prob > F
Without Armored Locations	26	0.6914	53.776	0.0001
Without Armored and Adjacent Armored Locations	16	0.7714	47.236	0.0001

TABLE 10.
Eigenvectors for PCA of 303-Location Original Data Set (8 Parameters)

	Principal Component 1	**Principal Component 2**	**Principal Component 3**
Wave Power	0.508313	-0.031429	0.020671
Nearshore Bathymetry	0.499742	0.152905	0.109398
Shoreline Exposure	0.559132	0.125539	0.148646
Nearshore Morphology	-0.170688	0.540919	-0.274929
Bank Height	0.105111	-0.624321	-0.159205
Bank Cover	-0.053693	0.492066	0.339302
Shoreline Armoring	0.363979	0.163257	-0.551806
Adjacent Armoring	0.060835	-0.093385	0.667055

FIGURE 1.
Deepwater Wave Forecasting Curves as a Function of Wind Speed and Fetch Length
(Taken from 1977 Army Corps of Engineers Shoreline Management Handbook)

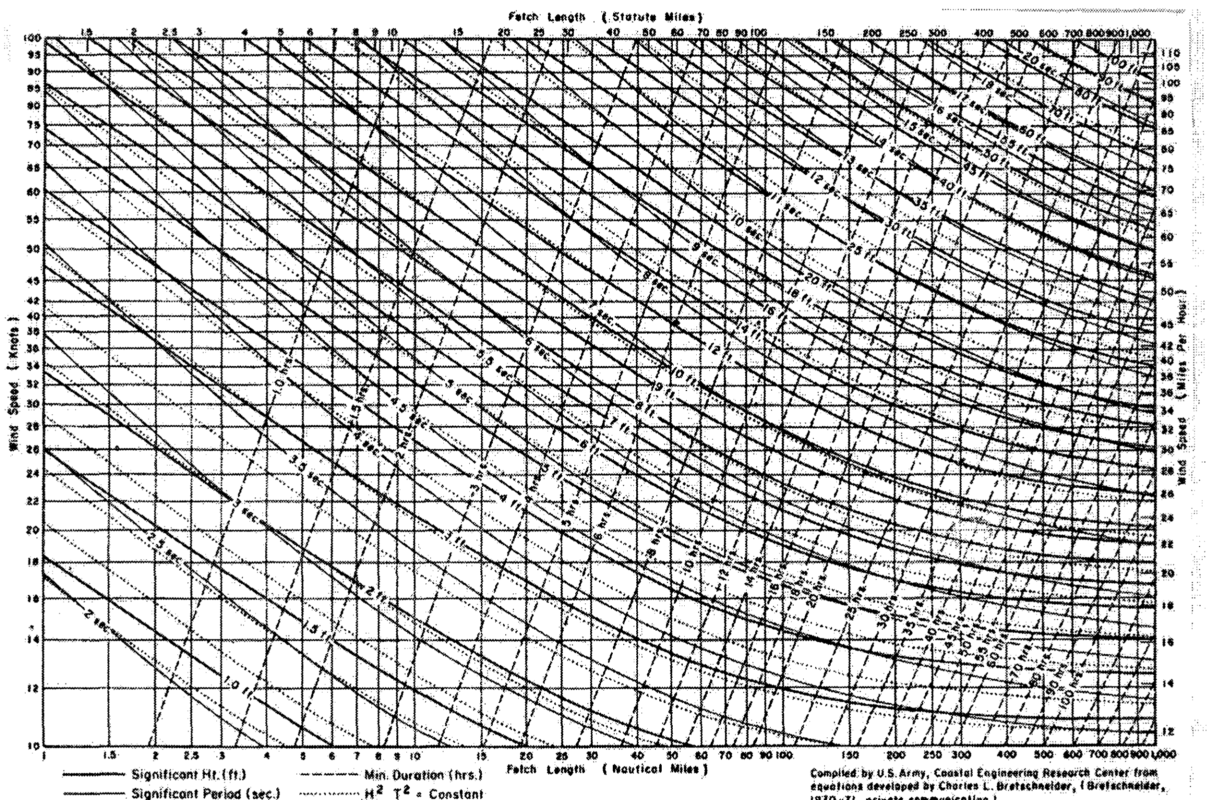


FIGURE 2.
Calibration and Validation Locations Used for Shoreline Instability Model

Model Calibration and Validation Sites for Shoreline Instability Model

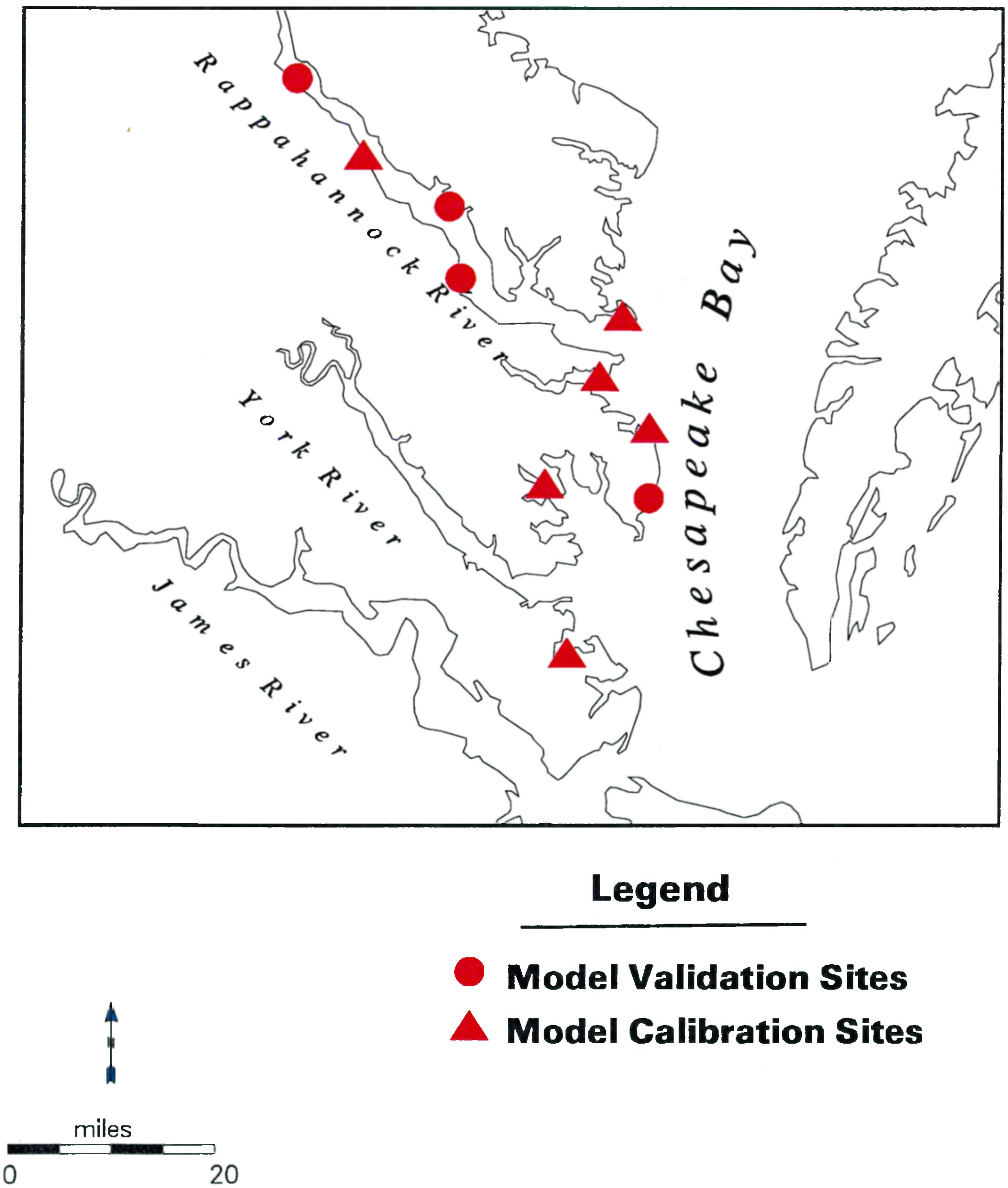
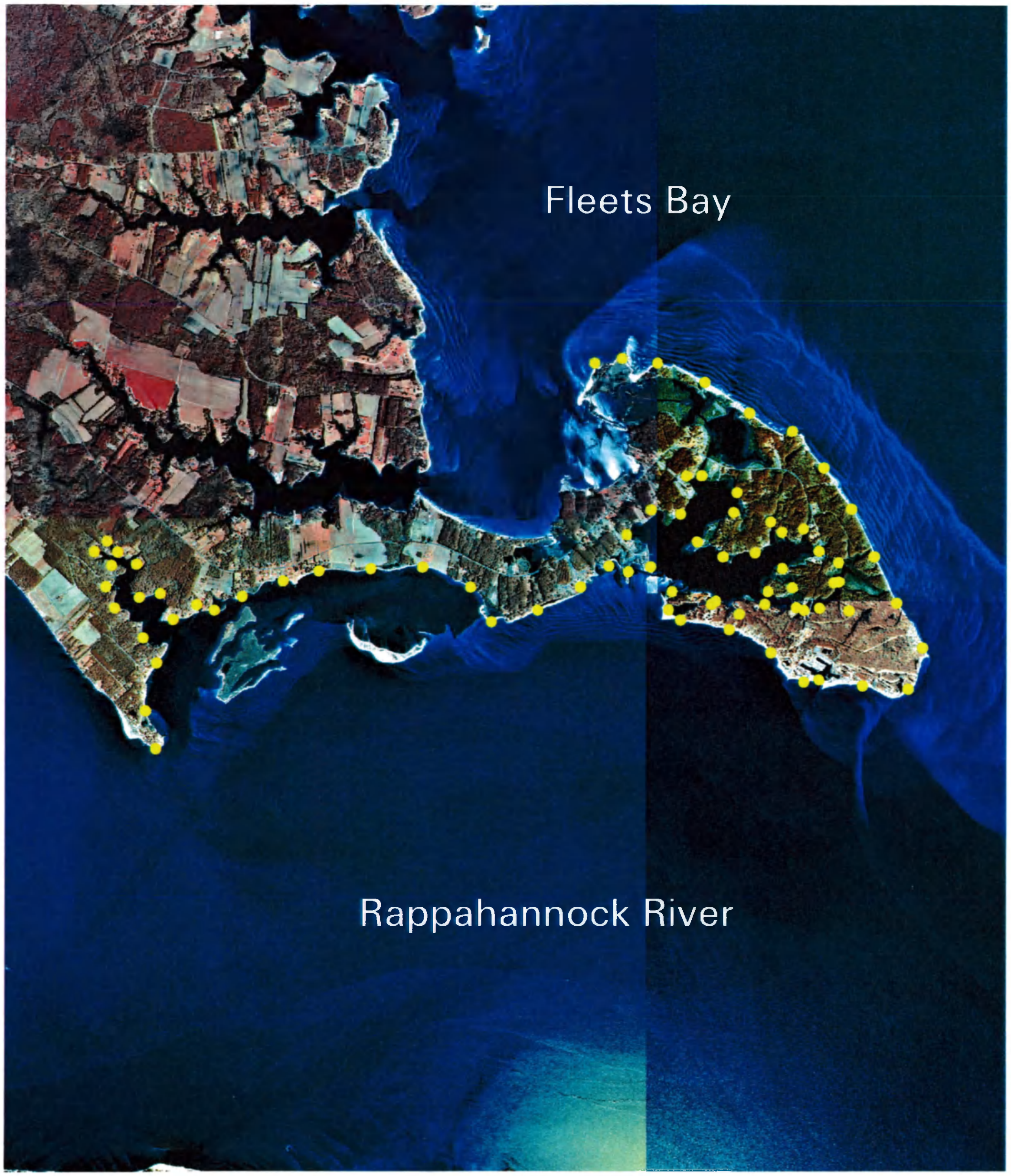


FIGURE 2A.
Lancaster County Model Calibration Site

Model Calibration Site
Lancaster County



Scale

0.5 0 Miles

1 : 61,000

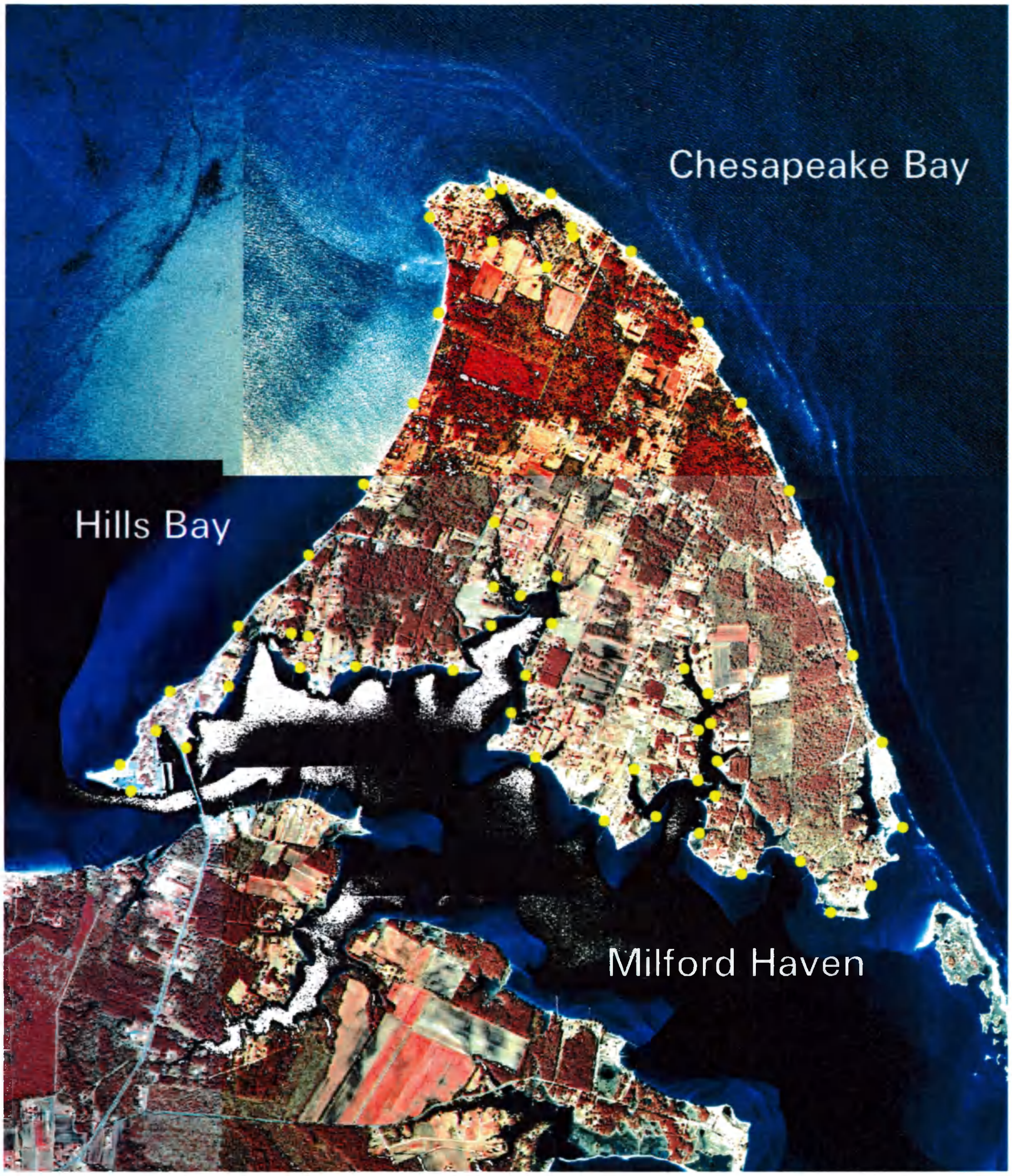
● Data Analysis Locations

FIGURE 2B.
Middlesex County Model Calibration Site

Model Calibration Site
Middlesex County

FIGURE 2C.
Mathews County Model Calibration Site

Model Calibration Site
Mathews County



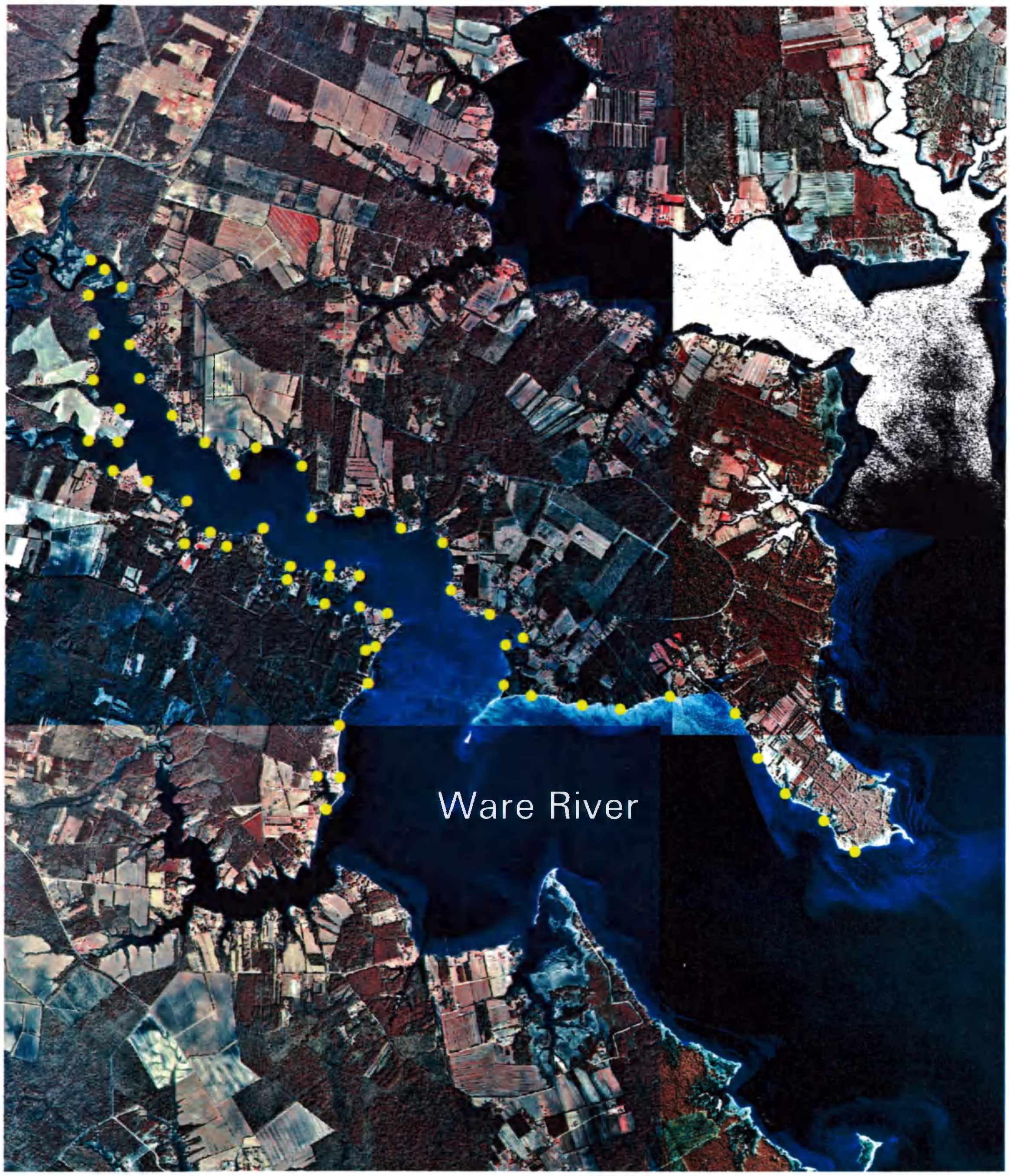
Scale

0.5 0 Miles

1 : 32,000

● Data Analysis Locations

Model Calibration Site
Gloucester County



Scale

0.5 0 Miles

1 : 61,000

● Data Analysis Locations

FIGURE 2E.
City of Poquoson Model Calibration Site

Model Calibration Site
City of Poquoson

Scale

0.5 Miles

1 : 26,000

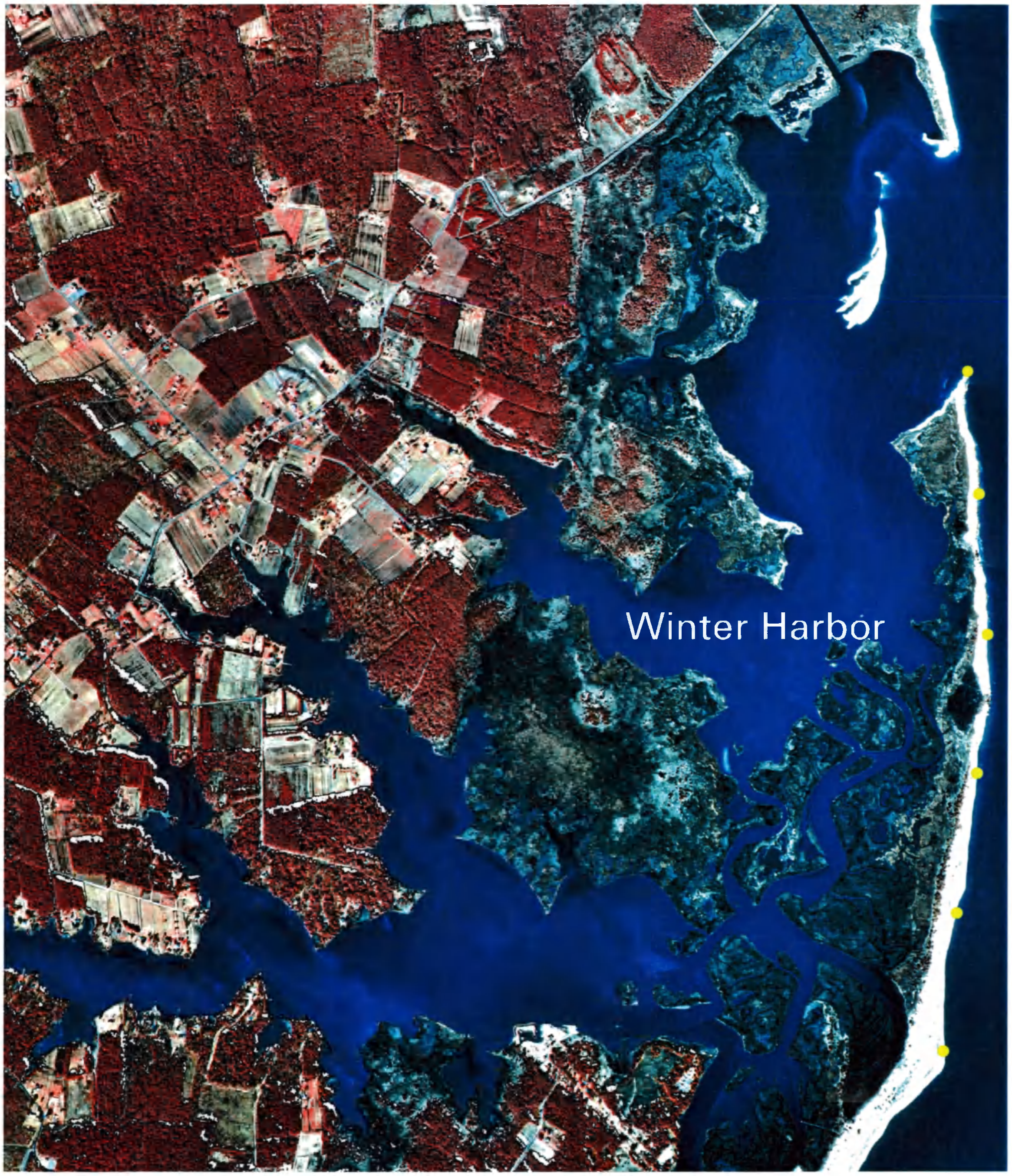
Data Analysis Locations

FIGURE 2F.
Essex County Model Calibration Site

Model Calibration Site
Essex County

FIGURE 2G.
Mathews County Model Validation Site

Model Validation Site
Mathews County



Scale

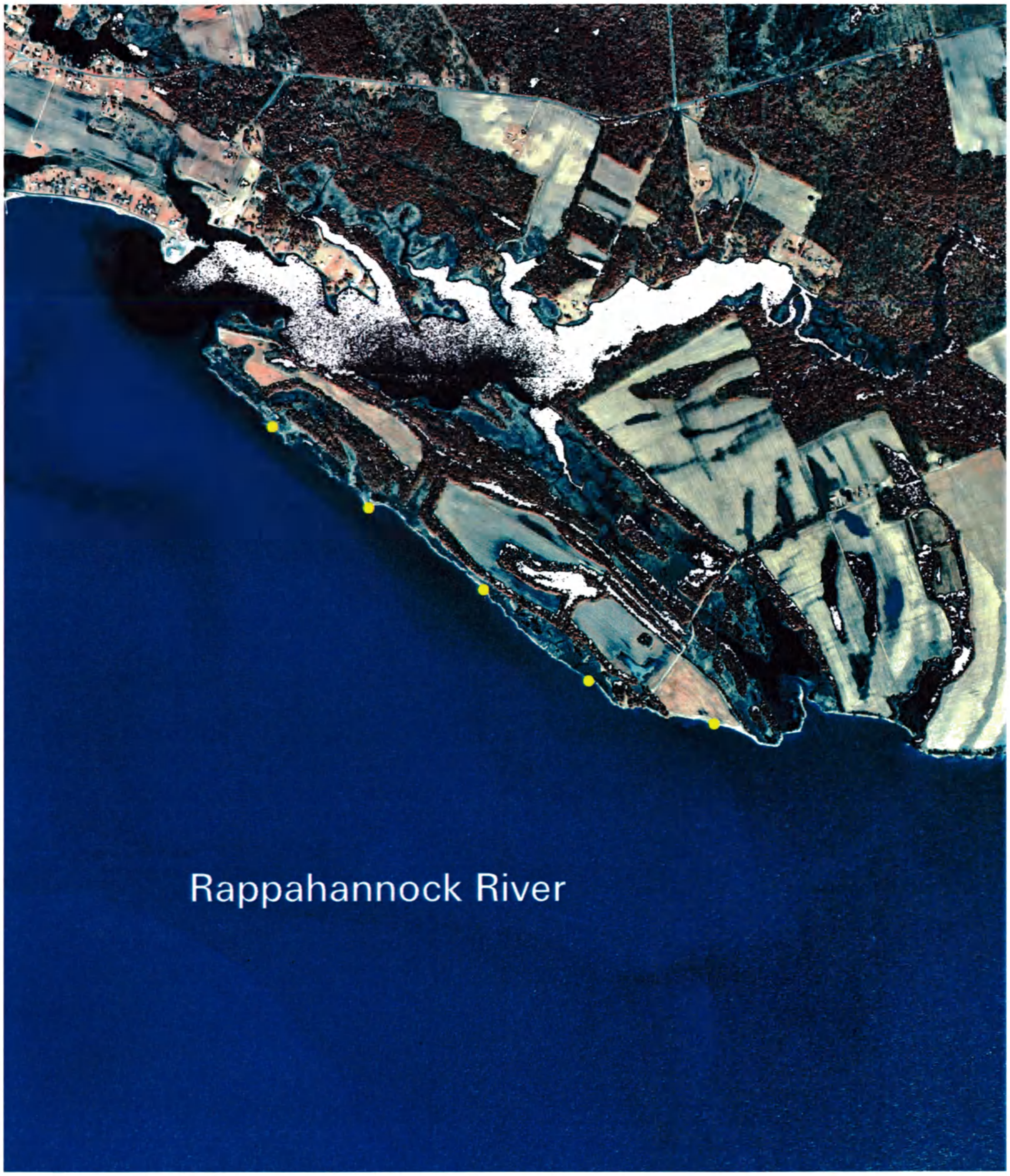
0.2 0 Miles

1 : 23,000

Data Analysis Locations

FIGURE 2H.
Lancaster County Model Validation Site

Model Validation Site
Lancaster County



Scale

Miles

0.2 0

1 : 23,000

Data Analysis Locations

FIGURE 2I.
Essex County Model Validation Site

Model Validation Site
Essex County

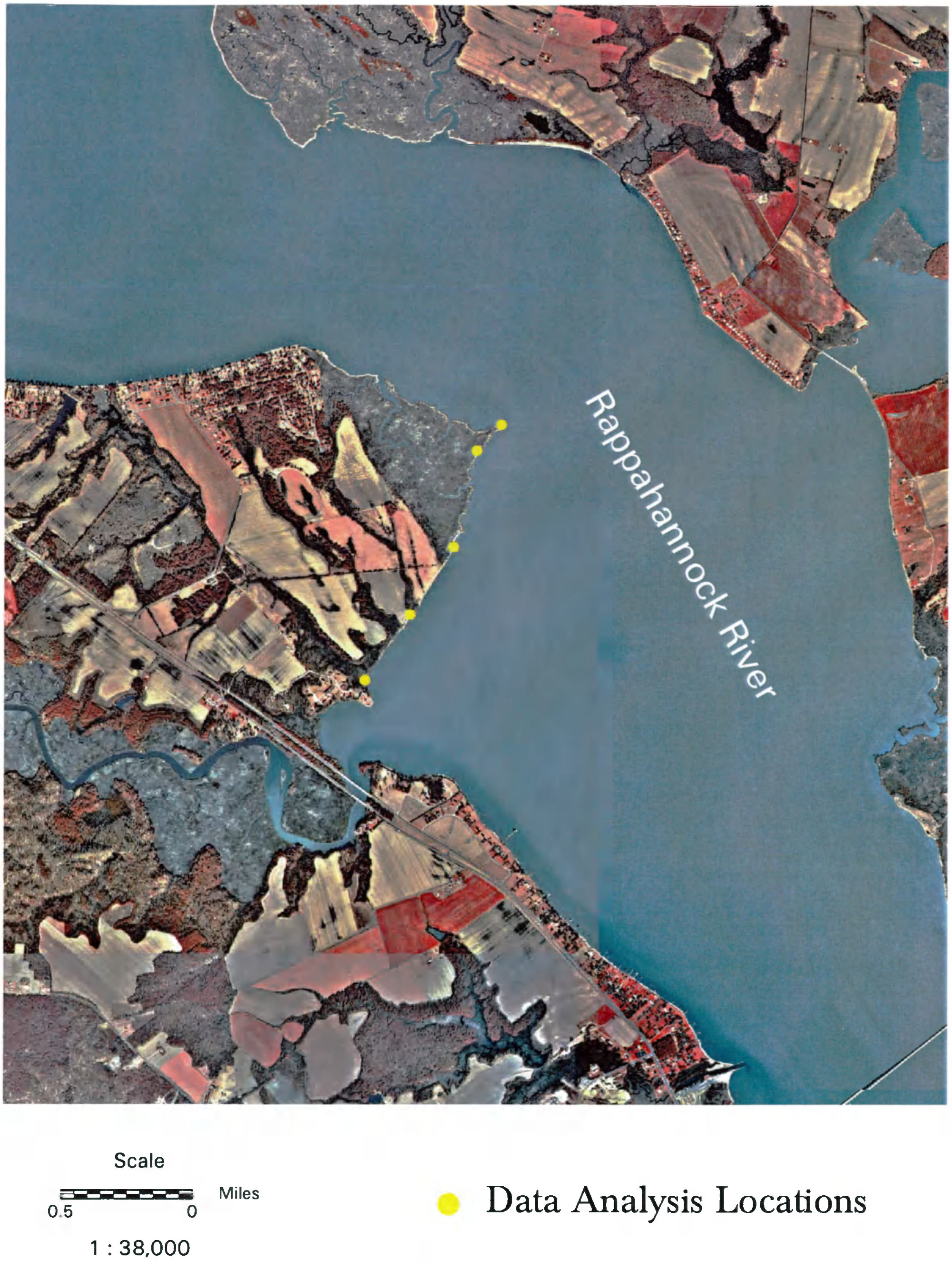


FIGURE 2J.
Middlesex County Model Validation Site

Model Validation Site
Middlesex County

Scale

0.2 0 Miles

1 : 23,000

● Data Analysis Locations

FIGURE 3.
Measured Rates of Shoreline Change for 303-Location Original Data Set
Based on Predicted Shoreline Instability Factors (6-Parameter Model)

Measured Rates of Shoreline Change for 303-Location Original Data Set
Based on Predicted Shoreline Instability Factors (6-Parameter Model)

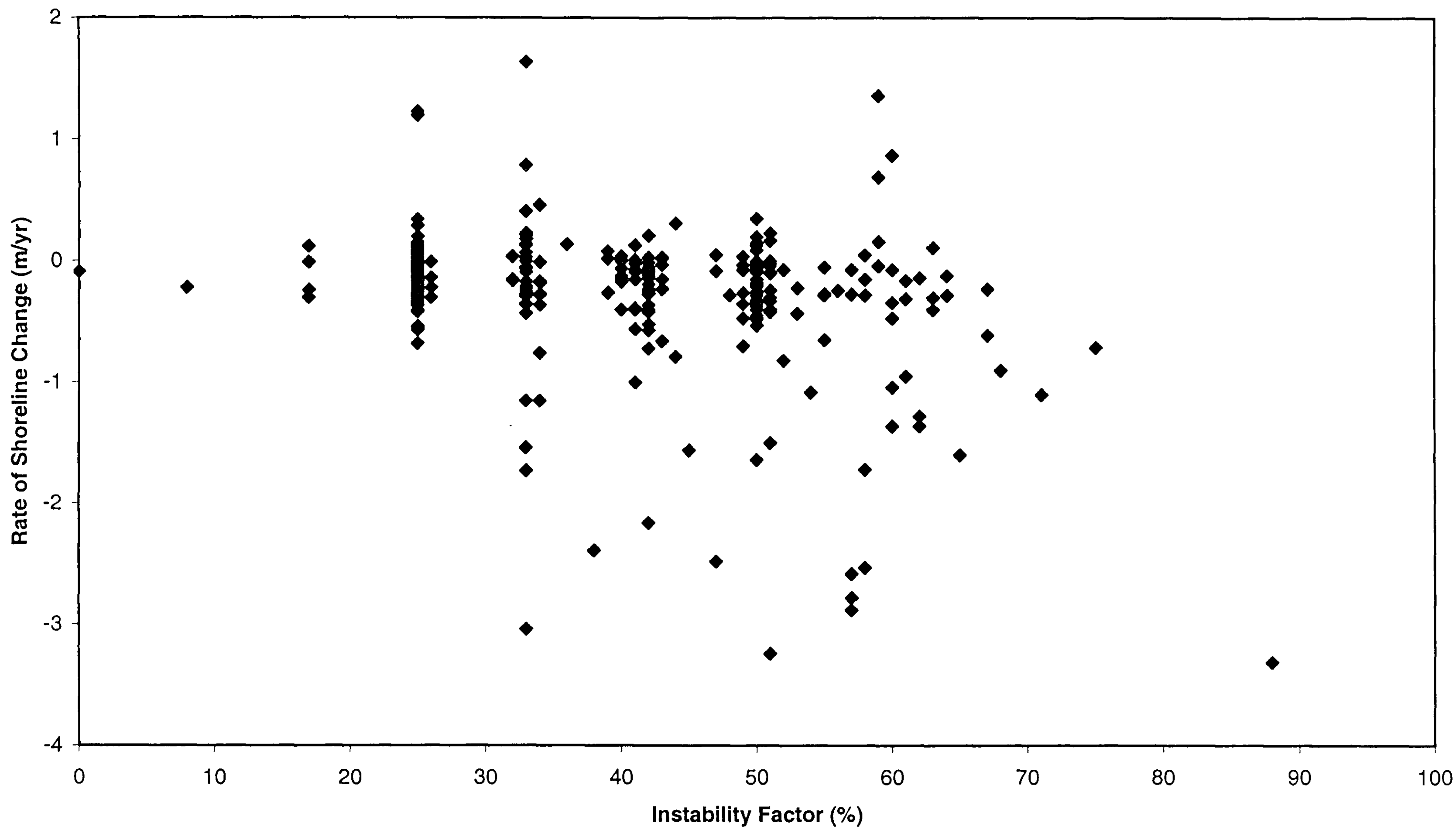


FIGURE 4.

Measured Rates of Shoreline Change for 70-Location Final Data Set
Based on Predicted Shoreline Instability Factors (6-Parameter Model)

Measured Rates of Shoreline Change for 70-Location Final Data Set
Based on Predicted Shoreline Instability Factors (6-Parameter Model)

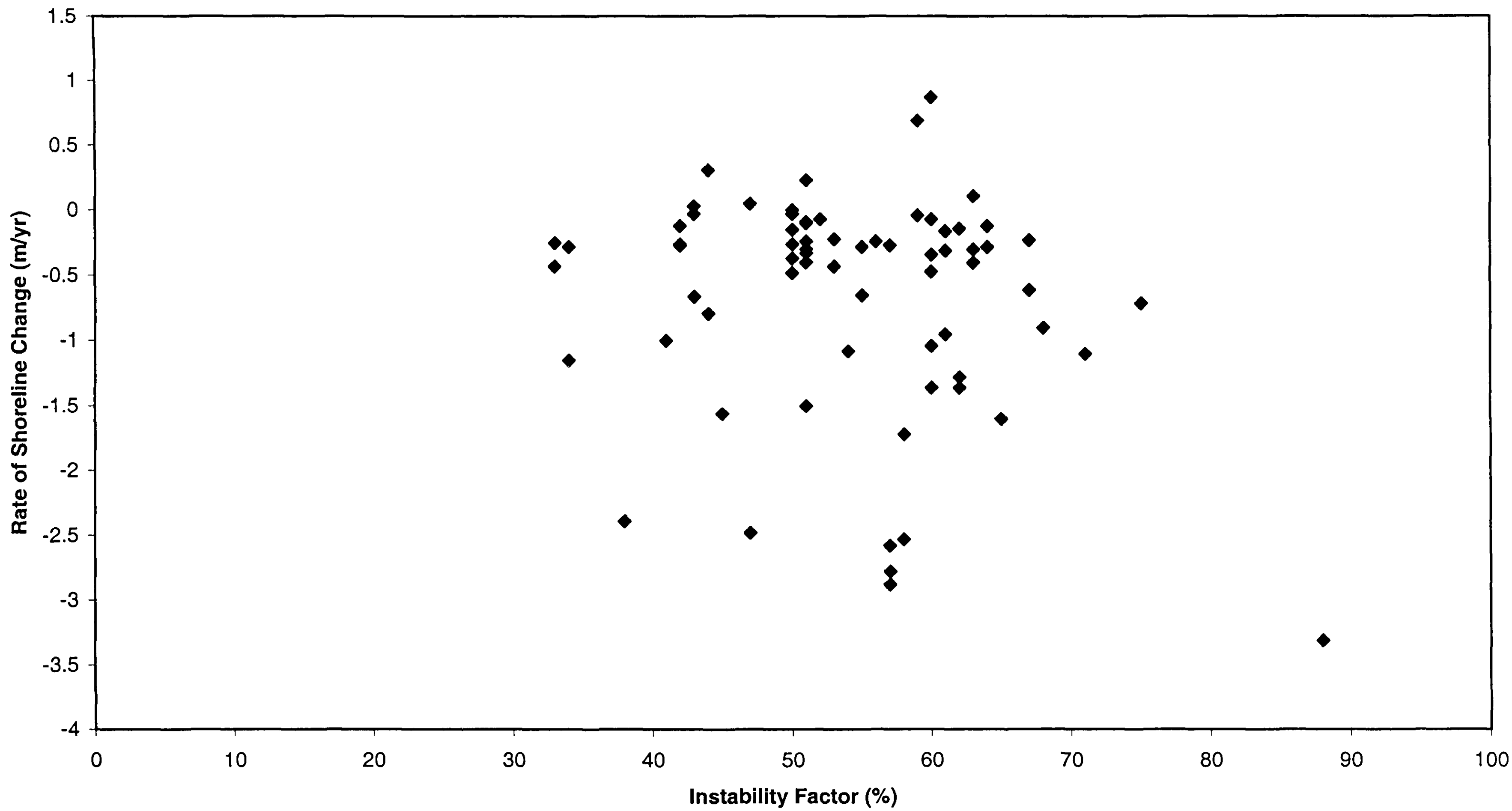


FIGURE 5.
Measured Rates of Shoreline Change for 70-Location Final Data Set
Based on Predicted Shoreline Instability Factors (3-Parameter Model)

Measured Rates of Shoreline Change for 70-Location Final Data Set
Based on Predicted Shoreline Instability Factors (3-Parameter Model)

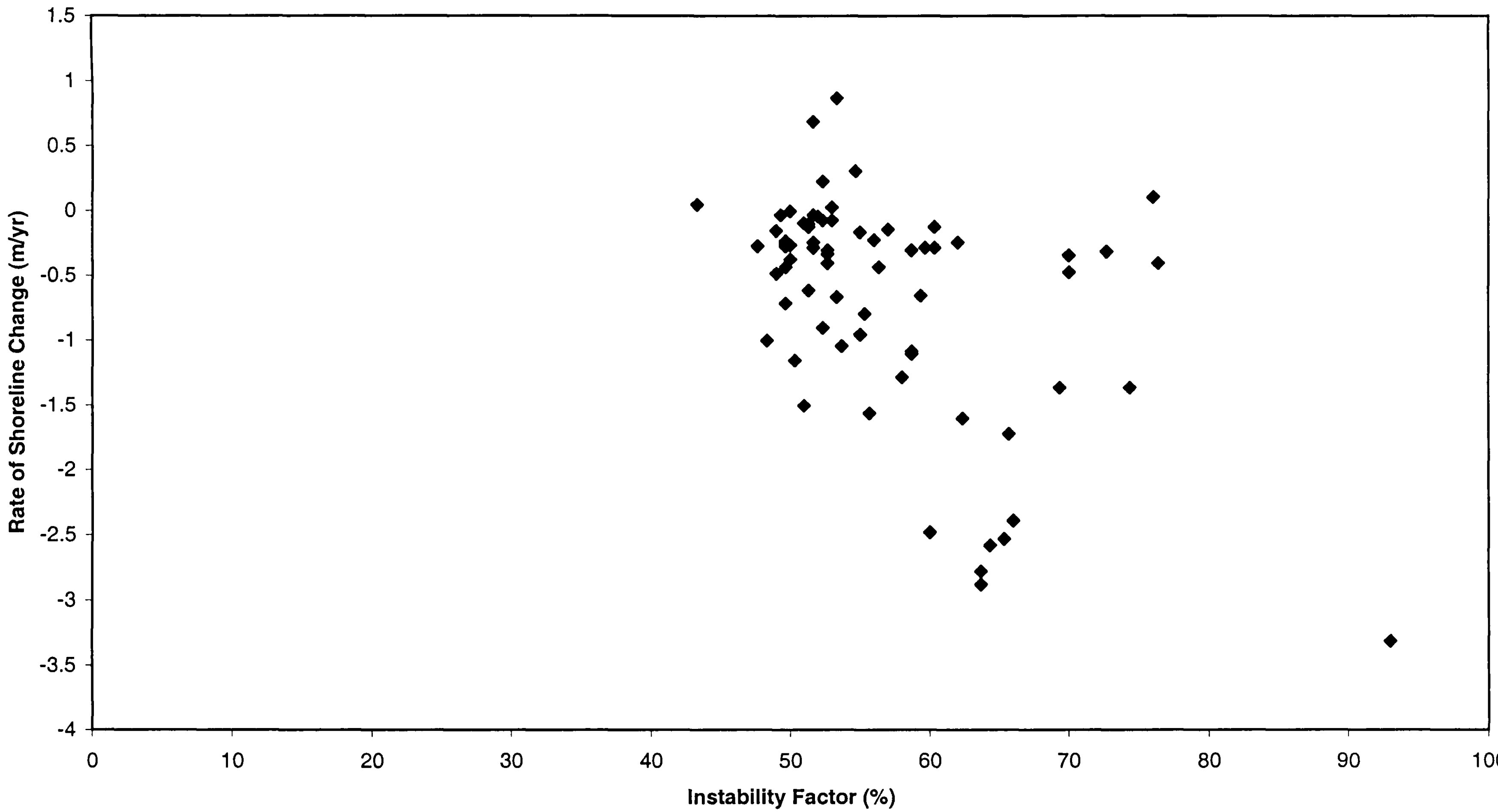


FIGURE 6.
Measured Rates of Shoreline Change for 70-Location Final Data Set Based on Predicted Shoreline Instability Factors (3-Parameter Model with Adjusted Weights)

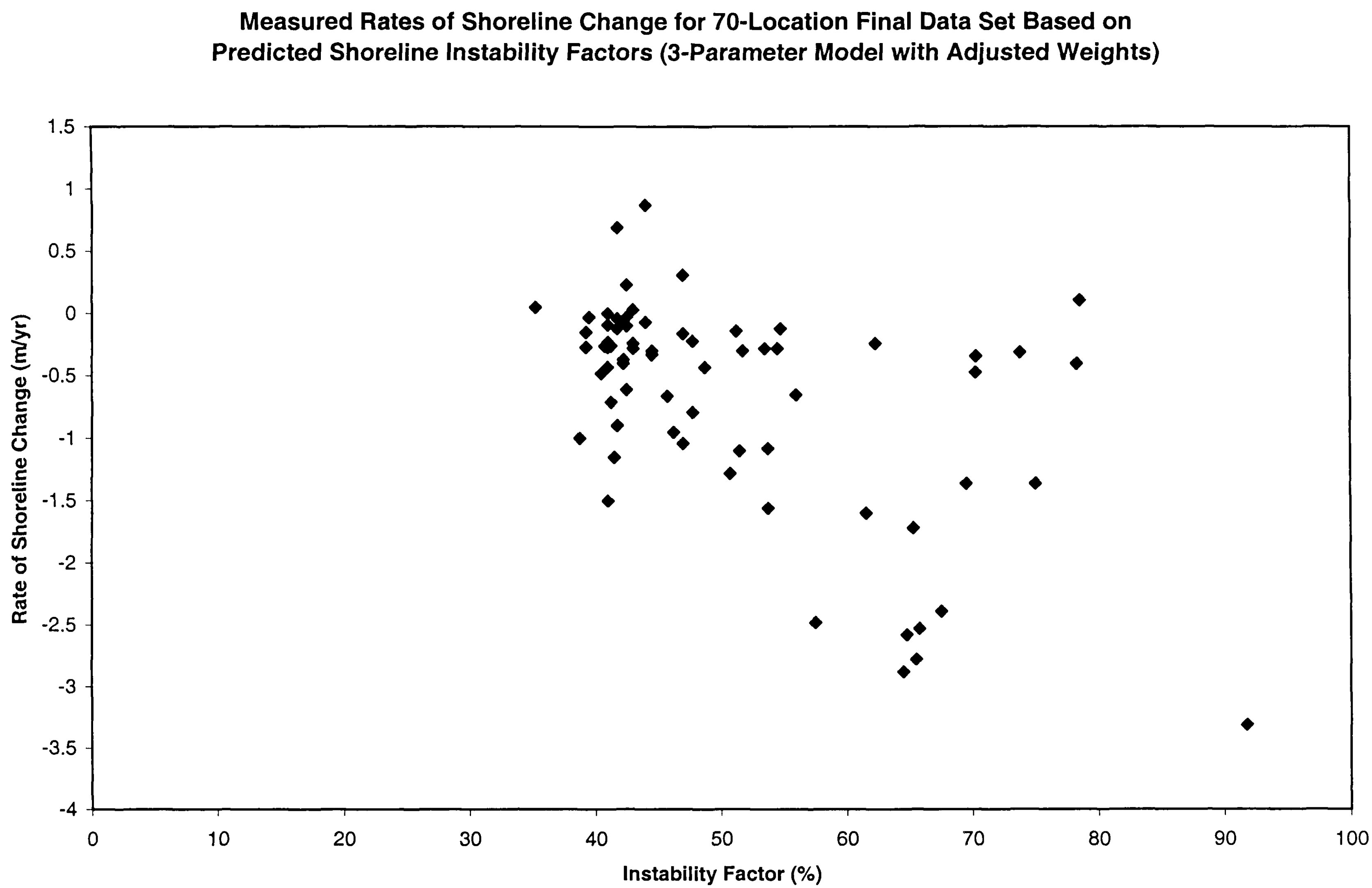

Measured Rates of Shoreline Change for 70-Location Final Data Set Based on
Predicted Shoreline Instability Factors (3-Parameter Model with Adjusted Weights)
Rate of Shoreline Change (m/yr)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0
10
20
30
40
50
60
70
80
90
100
Instability Factor (%)

FIGURE 7.
Measured Rates of Shoreline Change for 26 Locations of Final Data Set Without Shoreline Armoring Based on Predicted Shoreline Instability Factors (3-Parameter Model with Adjusted Weights)

Measured Rates of Shoreline Change for 26 Locations of Final Data Set Without Shoreline Armoring Based on Predicted Shoreline Instability Factors (3-Parameter Model with Adjusted Weights)

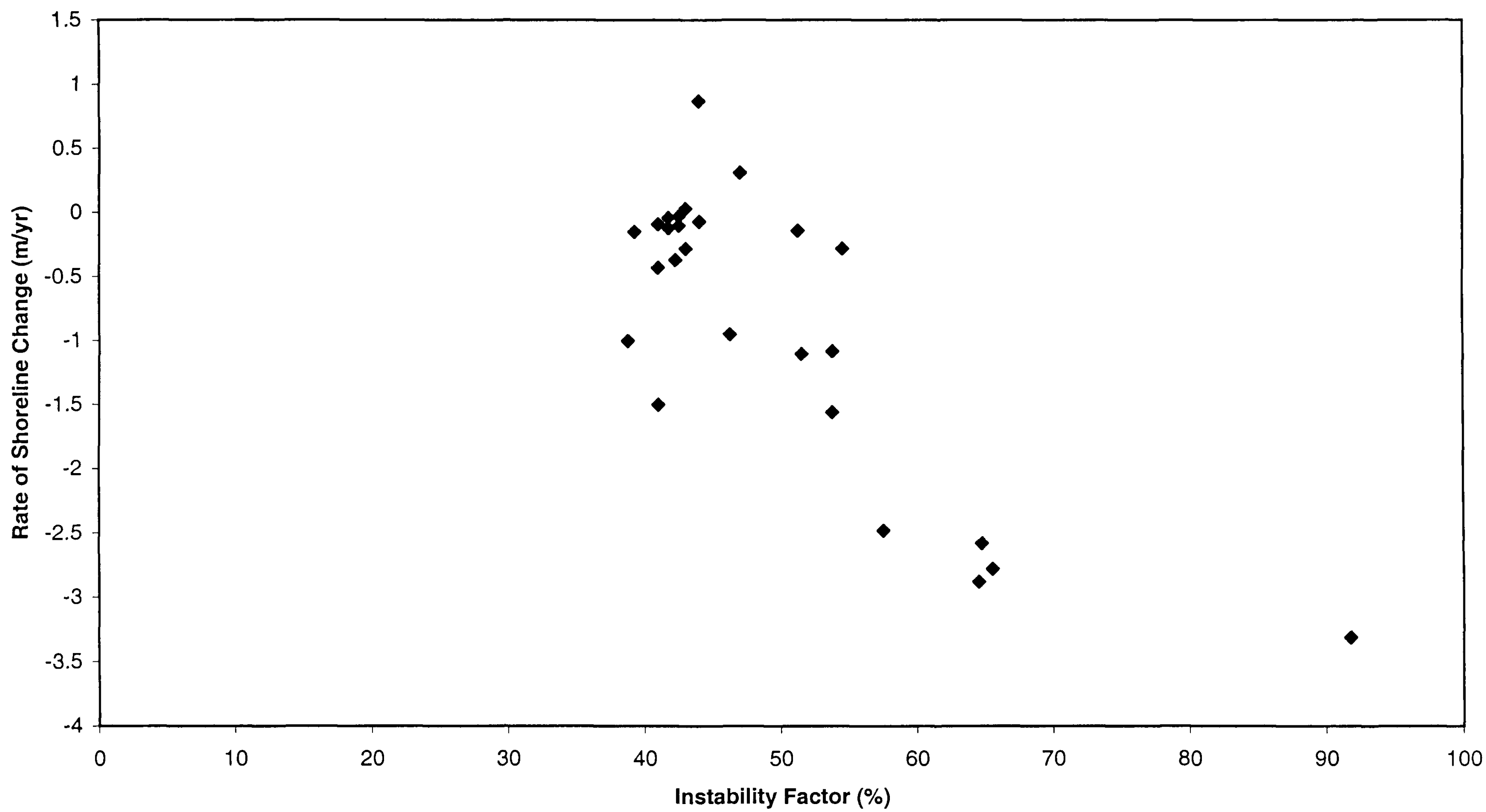


FIGURE 8.
Measured Rates of Shoreline Change for 16 Locations of Final Data Set Without Armoring or Adjacent Shoreline Armoring Based on Predicted Shoreline Instability Factors (3-Parameter Model with Adjusted Weights)

Measured Rates of Shoreline Change for 16 Locations of Final Data Set Without Armoring or Adjacent Shoreline Armoring Based on Predicted Shoreline Instability Factors (3-Parameter Model with Adjusted Weights)

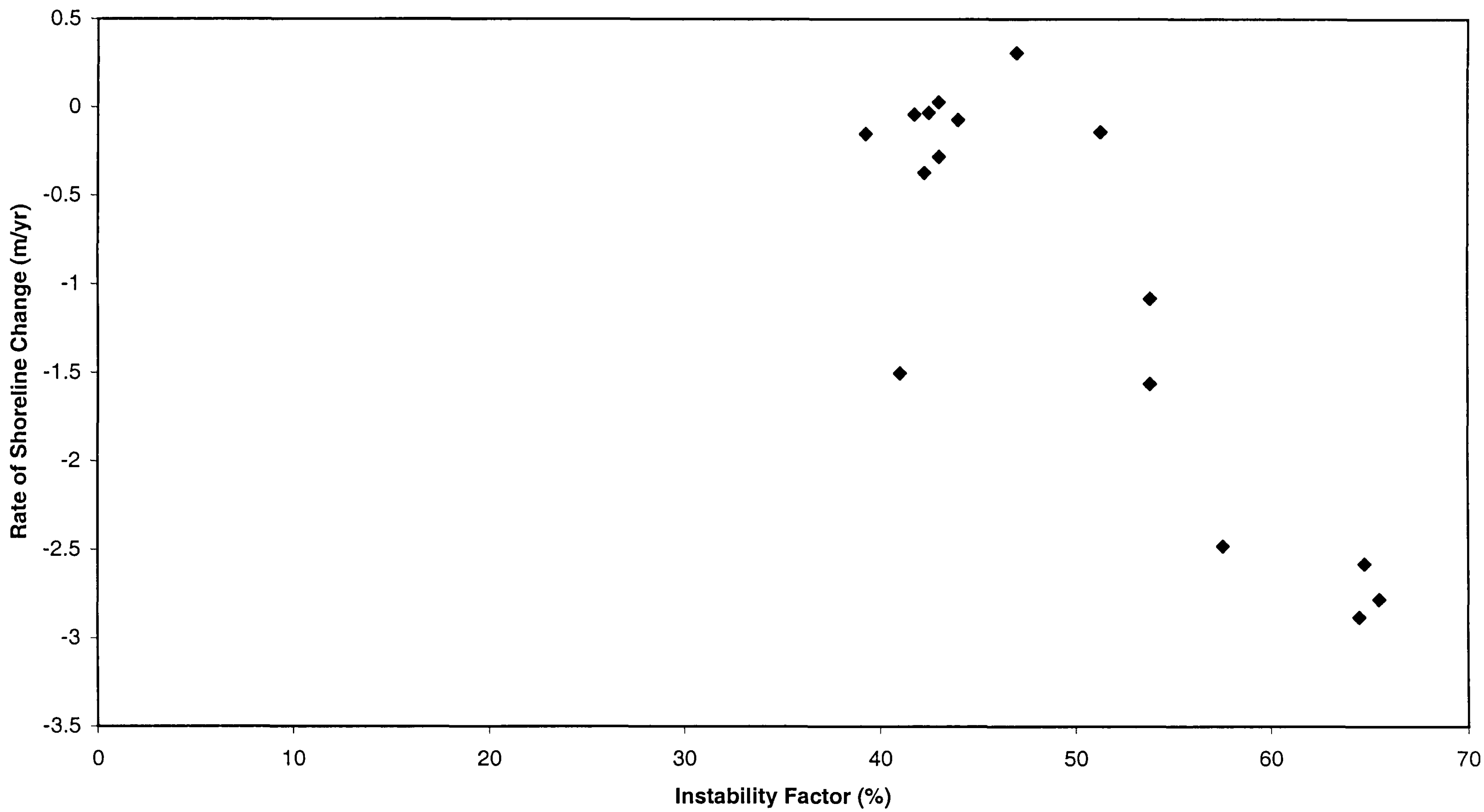
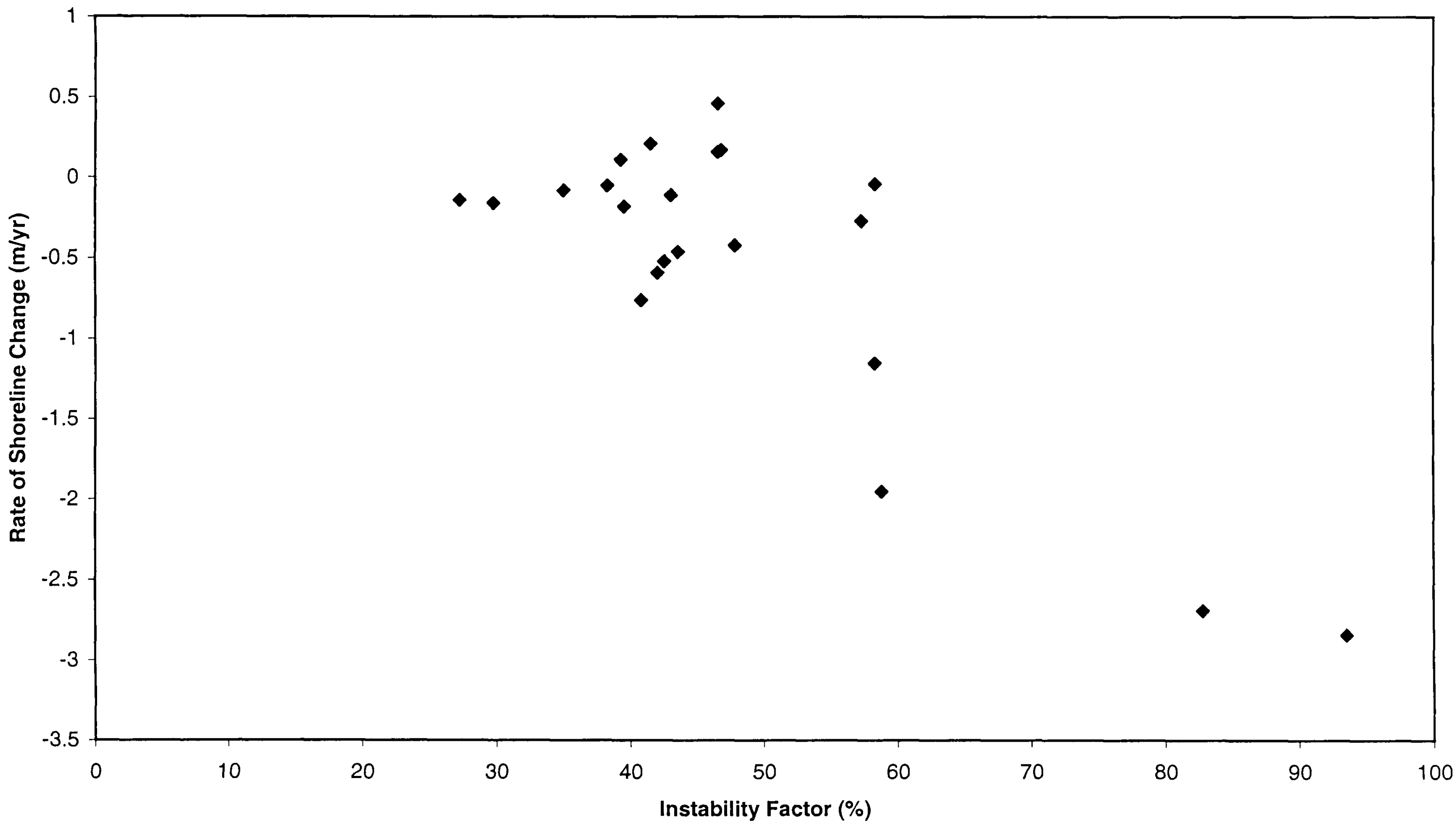


FIGURE 9.
Measured Rates of Shoreline Change for Model Validation Locations
Based on Predicted Shoreline Instability Factors
(3-Parameter Model with Adjusted Weights)

Measured Rates of Shoreline Change for Model Validation Locations Based on Predicted Shoreline Instability Factors (3-Parameter Model with Adjusted Weights)



APPENDIX I.

303-Location Original Model Calibration Data Set

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Middlesex	0	0	0	0	0	0	0	-0.09	residential	no	no
Middlesex	0	0	0	0	50	50	17	-0.3	forested	no	no
Middlesex	0	0	0	50	0	0	8	-0.22	residential	no	no
Middlesex	0	0	0	50	100	0	25	0.03	forested	no	no
Middlesex	0	0	0	50	100	0	25	0.34	scrub-shrub	no	no
Middlesex	0	0	0	50	100	50	33	-0.29	residential	no	no
Middlesex	0	0	0	50	100	50	33	0.41	forested	no	no
Middlesex	0	0	0	100	0	0	17	0.12	residential	no	no
Middlesex	0	0	0	100	0	50	25	-0.31	forested	no	bulkhead
Middlesex	0	0	0	100	0	50	25	-0.26	residential	no	no
Middlesex	0	0	0	100	0	50	25	-0.18	residential	no	riprap
Middlesex	0	0	0	100	0	50	25	-0.14	residential	no	no
Middlesex	0	0	0	100	0	50	25	-0.12	residential	no	no
Middlesex	0	0	0	100	0	50	25	-0.06	forested	no	no
Middlesex	0	0	0	100	0	50	25	-0.05	residential	no	no
Middlesex	0	0	0	100	0	50	25	0.09	forested	no	no
Middlesex	0	0	0	100	0	100	33	-0.28	residential	no	no
Middlesex	0	0	0	100	50	0	25	-0.35	residential	no	no
Middlesex	0	0	0	100	50	0	25	-0.34	residential	no	no
Middlesex	0	0	0	100	50	0	25	-0.18	forested	no	no
Middlesex	0	0	0	100	50	0	25	-0.08	forested	no	no
Middlesex	0	0	0	100	50	0	25	-0.03	forested	no	no
Middlesex	0	0	0	100	50	0	25	-0.02	forested	no	no
Middlesex	0	0	0	100	50	0	25	0	forested	no	no
Middlesex	0	0	0	100	50	50	33	-0.35	forested	no	no
Middlesex	0	0	0	100	50	50	33	-0.17	forested	no	no
Middlesex	0	0	0	100	50	50	33	-0.09	forested	no	no
Middlesex	0	0	0	100	50	50	33	-0.06	forested	no	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Middlesex	0	0	0	100	50	50	33	0.03	forested	no	no
Middlesex	0	0	0	100	100	0	33	0.13	forested	no	no
Middlesex	0	0	0	100	100	50	42	-0.19	forested	no	no
Middlesex	0	0	0	100	100	50	42	-0.11	forested	no	no
Mathews	0	0	0	50	100	0	25	-0.2	scrub-shrub	no	no
Mathews	0	0	0	50	100	0	25	-0.18	scrub-shrub	no	no
Mathews	0	0	0	50	100	0	25	-0.14	residential	no	no
Mathews	0	0	0	50	100	0	25	-0.12	residential	no	riprap
Mathews	0	0	0	50	100	0	25	-0.06	residential	no	no
Mathews	0	0	0	50	100	0	25	0.11	scrub-shrub	no	no
Mathews	0	0	0	50	100	0	25	0.29	residential	no	no
Mathews	0	0	0	50	100	50	33	-0.36	residential	marina	no
Mathews	0	0	0	50	100	50	33	0.21	residential	no	no
Mathews	0	0	0	100	100	0	33	-3.04	residential	no	no
Mathews	0	0	0	100	100	0	33	-1.73	residential	no	no
Mathews	0	0	0	100	100	0	33	-1.15	residential	no	no
Mathews	0	0	0	100	100	0	33	-0.21	residential	no	riprap
Mathews	0	0	0	100	100	0	33	-0.09	residential	riprap	no
Mathews	0	0	0	100	100	0	33	-0.06	residential	no	no
Mathews	0	0	0	100	100	0	33	-0.05	residential	riprap	no
Mathews	0	0	0	100	100	0	33	0.14	residential	no	no
Mathews	0	0	0	100	100	0	33	0.21	forested	no	no
Mathews	0	0	0	100	100	0	33	0.23	scrub-shrub	no	no
Lancaster	0	0	0	50	100	0	25	-0.57	forested	no	no
Lancaster	0	0	0	50	100	0	25	-0.55	residential	no	no
Lancaster	0	0	0	50	100	0	25	-0.37	residential	no	no
Lancaster	0	0	0	50	100	0	25	-0.33	residential	riprap	no
Lancaster	0	0	0	50	100	0	25	-0.22	forested	no	riprap

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Lancaster	0	0	0	50	100	0	25	-0.17	forested	no	bulkhead
Lancaster	0	0	0	50	100	0	25	-0.1	residential	no	no
Lancaster	0	0	0	50	100	0	25	0.07	forested	no	no
Lancaster	0	0	0	50	100	0	25	0.08	forested	no	no
Lancaster	0	0	0	50	100	0	25	0.13	forested	no	no
Lancaster	0	0	0	50	100	0	25	1.2	residential	no	bulkhead
Lancaster	0	0	0	50	100	0	25	1.23	forested	no	no
Lancaster	0	0	0	100	100	0	33	-0.09	residential	bulkhead	no
Lancaster	0	0	0	100	100	0	33	0.18	residential	riprap	no
Lancaster	0	0	0	100	100	0	33	0.79	residential	riprap	no
Lancaster	0	0	0	100	100	0	33	1.64	forested	bulkhead	no
Poquoson	0	0	0	50	100	0	25	-0.41	residential	no	riprap
Poquoson	0	0	0	50	100	0	25	-0.36	forested	no	riprap
Poquoson	0	0	0	50	100	0	25	-0.35	forested	no	no
Poquoson	0	0	0	50	100	0	25	-0.17	residential	riprap	no
Poquoson	0	0	0	50	100	0	25	-0.03	residential	bulkhead	no
Poquoson	0	0	0	50	100	0	25	0.15	forested	no	no
Poquoson	0	0	0	100	100	0	33	-0.27	residential	riprap	no
Poquoson	0	0	0	100	100	0	33	-0.26	residential	riprap	no
Poquoson	0	0	0	100	100	0	33	0	residential	no	riprap
Poquoson	0	0	0	100	100	0	33	0.07	residential	riprap	no
Gloucester	0	0	0	50	100	0	25	-0.35	forested	no	no
Gloucester	0	0	0	50	100	0	25	-0.24	grass	no	no
Gloucester	0	0	0	50	100	0	25	-0.09	forested	no	no
Gloucester	0	0	0	50	100	0	25	-0.01	residential	no	no
Gloucester	0	0	0	50	100	0	25	0.02	residential	no	no
Gloucester	0	0	0	50	100	0	25	0.05	scrub-shrub	no	no
Gloucester	0	0	0	50	100	0	25	0.2	forested	no	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Middlesex	0	92	0	50	50	0	32	-0.15	residential	no	no
Middlesex	0	94	0	100	50	0	41	-0.09	forested	no	no
Middlesex	0	97	0	50	50	50	41	0.01	forested	no	no
Middlesex	0	98	0	50	0	50	33	0.22	residential	riprap	no
Middlesex	0	98	0	100	0	50	41	-0.39	forested	no	no
Middlesex	0	98	0	100	50	50	50	-0.37	residential	no	no
Middlesex	0	99	0	50	0	50	33	0.18	forested	no	no
Middlesex	0	99	0	50	100	0	42	-0.42	scrub-shrub	no	no
Middlesex	0	99	0	50	100	0	42	-0.14	residential	riprap	no
Middlesex	0	99	0	100	0	0	33	-0.23	residential	no	no
Middlesex	0	99	0	100	50	50	50	0.15	residential	no	no
Middlesex	0	100	0	100	0	50	42	0.21	residential	no	no
Mathews	1	0	0	50	100	50	34	-0.27	residential	no	no
Mathews	1	0	0	100	100	0	34	-0.36	grass	no	bulkhead
Mathews	1	0	0	100	100	100	50	-0.09	residential	no	no
Lancaster	1	0	0	50	50	0	17	-0.01	forested	no	no
Lancaster	1	0	0	50	100	0	25	-0.68	residential	no	no
Lancaster	1	0	0	50	100	0	25	-0.29	forested	no	no
Lancaster	1	0	0	50	100	0	25	-0.23	scrub-shrub	no	no
Lancaster	1	0	0	50	100	0	25	-0.2	forested	no	no
Lancaster	1	0	0	50	100	0	25	-0.18	forested	no	no
Lancaster	1	0	0	50	100	0	25	-0.16	residential	no	no
Lancaster	1	0	0	50	100	0	25	-0.07	forested	no	no
Lancaster	1	0	0	50	100	0	25	-0.06	residential	riprap	no
Lancaster	1	0	0	50	100	0	25	-0.04	forested	no	no
Lancaster	1	0	0	100	100	0	33	-0.05	commercial	marina	no
Poquoson	1	0	0	50	100	0	25	-0.27	scrub-shrub	no	no
Poquoson	1	0	0	50	100	0	25	-0.13	residential	no	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Poquoson	1	0	0	50	100	0	25	-0.09	residential	bulkhead	no
Poquoson	1	0	0	100	100	0	34	-0.36	residential	no	no
Poquoson	1	0	0	100	100	0	34	-0.17	forested	no	no
Gloucester	1	0	0	50	50	0	17	-0.24	forested	no	no
Gloucester	1	0	0	50	100	0	25	-0.42	forested	no	no
Gloucester	1	0	0	50	100	0	25	-0.25	forested	no	no
Gloucester	1	0	0	50	100	0	25	-0.17	forested	no	no
Gloucester	1	0	0	50	100	0	25	-0.09	residential	no	no
Gloucester	1	0	0	50	100	0	25	-0.05	forested	no	no
Gloucester	1	0	0	50	100	0	25	0	forested	no	no
Gloucester	1	0	0	50	100	0	25	0.13	forested	no	no
Gloucester	1	48	50	50	100	0	42	-0.05	residential	no	no
Gloucester	1	62	0	50	100	0	36	0.14	forested	no	no
Lancaster	1	82	0	50	100	0	39	-0.26	forested	no	no
Lancaster	1	82	0	50	100	0	39	0.08	forested	no	no
Gloucester	1	84	0	50	100	0	39	0.02	residential	no	no
Mathews	1	87	0	50	100	0	40	0	residential	riprap	no
Lancaster	1	87	0	50	100	0	40	-0.12	forested	no	bulkhead
Gloucester	1	87	0	50	100	0	40	0.04	residential	no	no
Poquoson	1	93	0	50	100	0	41	-0.15	forested	no	no
Middlesex	1	97	0	100	100	0	50	-0.01	scrub-shrub	no	no
Mathews	1	97	0	50	100	0	41	0.13	residential	no	bulkhead
Mathews	1	98	0	100	100	0	50	-0.47	forested	no	no
Middlesex	1	99	0	50	100	50	50	0.35	residential	bulkhead	no
Middlesex	1	99	0	100	0	50	42	-0.36	forested	no	no
Middlesex	1	99	0	100	50	100	58	-0.15	residential	no	no
Lancaster	2	0	0	50	100	0	25	-0.54	residential	no	riprap
Lancaster	2	0	0	50	100	0	25	-0.27	residential	no	bulkhead

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Lancaster	2	0	0	50	100	0	25	-0.15	scrub-shrub	no	no
Lancaster	2	0	0	50	100	0	25	-0.09	forested	no	riprap
Gloucester	2	0	0	50	100	0	25	-0.03	forested	no	no
Gloucester	2	0	0	50	100	0	25	0.15	residential	no	no
Gloucester	2	85	0	50	100	0	40	-0.06	residential	no	no
Gloucester	2	85	0	50	100	0	40	0.01	forested	no	bulkhead
Lancaster	2	91	0	50	100	0	41	-0.07	forested	no	bulkhead
Gloucester	2	91	50	50	100	0	49	-0.03	residential	bulkhead	no
Lancaster	2	95	0	50	100	0	41	-0.4	forested	no	no
Middlesex	2	97	0	100	50	0	42	-2.16	residential	riprap	no
Mathews	2	98	0	50	100	0	42	0.03	commercial	riprap	no
Mathews	2	98	0	100	100	0	50	-0.35	residential	riprap	no
Lancaster	2	98	0	50	100	0	42	-0.14	forested	no	no
Middlesex	2	99	0	100	100	0	50	-0.25	residential	no	no
Gloucester	3	0	0	50	100	0	26	-0.14	scrub-shrub	no	bulkhead
Gloucester	3	0	50	50	100	50	42	-0.07	forested	no	no
Lancaster	3	95	0	50	100	0	41	-0.56	forested	no	no
Lancaster	3	96	50	50	100	0	50	-0.53	forested	no	riprap
Middlesex	3	97	0	0	100	0	33	0.03	residential	no	no
Mathews	3	97	0	50	100	0	42	-0.72	residential	no	riprap
Mathews	3	97	0	50	100	0	42	-0.23	residential	bulkhead	no
Mathews	3	97	0	100	100	0	42	-0.57	residential	riprap	no
Lancaster	3	98	0	50	100	0	42	-0.4	forested	no	no
Gloucester	3	98	50	50	100	0	50	-0.04	residential	no	bulkhead
Middlesex	3	99	50	100	0	50	50	-0.32	forested	no	no
Gloucester	3	99	50	50	100	0	50	-0.28	residential	no	no
Mathews	3	100	0	100	100	0	50	0.2	commercial	marina	no
Gloucester	4	0	0	50	100	0	26	-0.22	residential	no	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Gloucester	4	0	50	50	100	0	34	-0.18	residential	no	no
Gloucester	4	73	50	50	100	50	55	-0.05	residential	riprap	no
Gloucester	4	88	0	50	100	50	49	0.04	residential	no	no
Gloucester	4	88	50	50	100	0	49	-0.07	forested	no	no
Gloucester	4	91	0	50	100	0	41	-0.02	residential	bulkhead	no
Gloucester	4	94	50	50	100	0	50	0.13	scrub-shrub	no	no
Mathews	4	95	50	100	100	0	58	-0.28	residential	riprap	no
Gloucester	4	95	50	50	100	0	50	0.09	forested	no	no
Mathews	4	96	50	100	100	0	58	0.05	residential	riprap	no
Mathews	4	97	0	100	100	0	50	-0.21	residential	riprap	no
Mathews	4	97	0	100	100	0	50	-0.08	residential	riprap	no
Gloucester	4	97	50	50	100	0	50	-0.05	residential	riprap	no
Gloucester	4	97	50	50	100	0	50	-0.03	residential	riprap	no
Lancaster	4	98	0	50	100	0	42	-0.09	scrub-shrub	no	no
Middlesex	4	99	50	50	0	0	34	0.46	forested	no	no
Middlesex	4	99	50	50	50	0	42	-0.52	residential	no	no
Middlesex	4	99	50	100	50	0	59	-0.04	forested	no	no
Poquoson	5	0	0	100	100	0	34	-0.76	forested	no	no
Essex	5	84	0	50	50	0	32	-0.16	residential	bulkhead,groin	no
Essex	5	84	0	100	50	0	40	-0.17	residential	riprap	no
Poquoson	5	84	0	50	100	50	48	-0.28	scrub-shrub	no	riprap
Mathews	5	92	0	100	100	0	50	-0.18	residential	riprap	no
Gloucester	5	97	50	50	100	0	50	-0.07	forested	no	no
Gloucester	5	97	50	50	100	0	50	0	residential	riprap	no
Middlesex	5	98	50	50	0	0	34	-0.01	forested	no	no
Mathews	5	98	50	50	100	0	51	-0.42	residential	no	riprap
Gloucester	5	98	50	50	100	0	51	0.17	forested	no	no
Middlesex	5	99	0	0	50	0	26	-0.01	residential	no	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Lancaster	6	0	0	50	100	0	26	-0.3	forested	no	no
Essex	6	85	50	50	100	0	49	-0.47	scrub-shrub	no	bulkhead,groin
Middlesex	6	96	0	50	100	0	42	-0.13	residential	riprap	no
Middlesex	6	96	50	50	100	0	50	-0.4	forested	no	no
Gloucester	6	96	50	50	100	0	50	-0.2	residential	riprap	no
Gloucester	6	97	50	50	100	0	51	-0.42	forested	no	riprap
Middlesex	6	99	50	100	0	0	43	0.02	residential	no	bulkhead
Essex	7	75	50	100	100	0	55	-0.27	residential	riprap	no
Lancaster	7	80	0	50	100	0	40	-0.4	forested	no	no
Gloucester	7	89	50	50	100	0	49	-0.35	residential	no	no
Lancaster	7	91	0	100	100	0	50	-0.15	residential	riprap	groin
Poquoson	7	91	50	50	100	0	50	-0.32	residential	no	riprap
Middlesex	7	94	50	100	50	0	50	-1.64	residential	bulkhead	no
Middlesex	7	95	50	100	0	0	42	-0.08	residential	riprap	no
Middlesex	7	96	50	50	0	100	51	-0.04	residential	no	no
Gloucester	7	97	50	50	100	0	51	0	residential	bulkhead	no
Middlesex	7	98	50	100	0	100	59	0.16	residential	no	bulkhead
Middlesex	7	99	50	100	0	0	43	-0.23	residential	bulkhead	no
Essex	8	76	50	50	100	0	47	-0.08	scrub-shrub	no	riprap
Lancaster	8	81	0	50	100	0	40	-0.14	scrub-shrub	no	no
Essex	8	86	50	100	100	0	57	-0.07	residential	riprap	no
Gloucester	8	88	0	0	100	50	42	-0.07	forested	no	no
Gloucester	8	91	50	0	100	0	42	-0.09	forested	no	no
Poquoson	8	94	50	50	100	0	50	-0.45	residential	riprap	no
Gloucester	8	95	0	50	100	0	42	-0.01	residential	no	riprap
Middlesex	8	97	50	50	100	0	51	-0.02	residential	riprap	no
Lancaster	9	84	0	0	100	0	32	0.04	residential	no	no
Essex	9	84	50	100	50	0	49	-0.26	residential	no	bulkhead,groin

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Middlesex	9	93	50	0	100	50	50	-0.34	residential	no	no
Middlesex	9	93	50	100	50	0	50	-0.19	residential	riprap	no
Middlesex	9	95	50	50	100	50	59	1.36	scrub-shrub	riprap	jetty
Middlesex	9	98	50	100	0	0	43	-0.15	residential	no	bulkhead
Essex	10	85	50	0	100	0	41	-1	residential	no	groin
Essex	10	87	50	50	100	0	50	-0.15	scrub-shrub	no	no
Essex	10	88	50	50	100	0	50	-0.03	residential	riprap	no
Lancaster	10	92	0	50	100	0	42	-0.24	residential	riprap	no
Middlesex	10	97	50	100	50	100	68	-0.9	residential	riprap	no
Middlesex	11	0	50	100	50	0	52	-0.82	residential	no	bulkhead
Essex	11	69	50	50	100	0	47	0.05	residential	bulkhead	no
Lancaster	11	82	0	100	100	0	49	-0.7	residential	no	no
Lancaster	11	85	0	0	100	0	33	-1.54	scrub-shrub	no	marina
Middlesex	11	92	50	100	50	0	51	-1.5	residential	no	no
Gloucester	11	92	50	50	100	0	51	-0.09	forested	no	riprap
Gloucester	11	95	50	50	100	50	59	-0.04	residential	no	no
Lancaster	11	97	50	50	100	0	51	-0.4	residential	bulkhead,groin	no
Lancaster	12	92	50	50	100	0	51	-3.24	scrub-shrub	no	no
Mathews	12	93	50	50	100	50	59	0.69	residential	riprap	no
Gloucester	12	95	50	50	100	0	52	-0.07	residential	bulkhead	no
Mathews	13	91	50	50	50	0	42	-0.12	residential	no	groin
Mathews	13	94	50	100	50	0	51	0.23	residential	groin	no
Essex	13	96	50	0	100	0	43	0.03	scrub-shrub	no	no
Essex	14	79	50	100	100	0	57	-0.27	residential	bulkhead	no
Essex	14	85	50	100	50	0	50	-0.26	grass	riprap	no
Mathews	14	86	50	100	50	0	50	0	residential	riprap	no
Essex	15	82	50	50	100	0	50	-0.48	residential	groin	bulkhead
Mathews	15	84	50	100	100	50	67	-0.23	scrub-shrub	riprap	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Essex	15	84	50	50	0	0	33	-0.43	residential	no	bulkhead,groin
Essex	15	84	50	50	0	0	33	-0.25	residential	bulkhead,groin	no
Essex	15	84	50	100	0	0	42	-0.27	residential	bulkhead,groin	no
Essex	15	85	50	100	0	0	42	-0.26	residential	bulkhead	no
Essex	15	86	50	50	0	0	34	-1.15	residential	riprap	no
Essex	15	90	50	0	100	0	43	-0.03	scrub-shrub	no	no
Mathews	16	83	50	100	100	100	75	-0.71	scrub-shrub	riprap	no
Mathews	16	88	50	100	100	50	67	-0.61	residential	groin	no
Lancaster	16	88	50	50	100	0	51	-0.1	residential	no	riprap,groin
Mathews	16	94	50	50	100	50	60	0.87	commercial	no	riprap
Lancaster	17	88	50	50	100	0	51	-0.24	residential	groin	no
Essex	17	88	50	0	50	0	34	-0.28	residential	no	no
Lancaster	17	92	50	100	100	0	60	-0.07	scrub-shrub	no	no
Essex	19	81	50	50	100	0	50	-0.37	forested	no	no
Mathews	20	88	50	100	50	0	51	-0.33	residential	groin	no
Essex	20	88	50	50	100	0	51	-0.3	residential	groin	no
Lancaster	20	95	50	100	100	0	61	-0.95	residential	no	riprap,groin
Lancaster	23	87	50	100	0	0	43	-0.66	forested	riprap	no
Lancaster	23	92	50	100	100	0	61	-0.16	residential	riprap	no
Lancaster	23	95	50	50	100	0	53	-0.22	residential	riprap	no
Lancaster	24	90	50	0	100	0	44	0.31	residential	no	no
Lancaster	25	91	50	0	100	0	44	-0.79	residential	riprap,groin	no
Lancaster	26	93	50	50	100	0	53	-0.43	residential	groin	riprap
Lancaster	27	84	50	100	100	0	60	-1.04	residential	riprap	no
Lancaster	29	95	50	100	100	0	62	-1.28	residential	riprap,groin	groin
Lancaster	30	96	50	50	100	100	71	-1.1	commercial	no	groin
Gloucester	31	95	50	50	100	50	63	-0.3	residential	bulkhead	no
Gloucester	34	87	50	50	100	50	62	-0.14	forested	no	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Gloucester	35	94	50	50	100	0	55	-0.28	residential	riprap	no
Gloucester	37	94	50	50	100	50	64	-0.28	residential	no	riprap
Gloucester	38	93	50	50	100	50	64	-0.12	residential	riprap	no
Lancaster	39	87	50	50	100	0	54	-1.08	scrub-shrub	no	no
Poquoson	46	82	50	50	100	0	55	-0.65	residential	riprap	no
Lancaster	48	69	50	0	100	0	45	-1.56	scrub-shrub	no	no
Lancaster	50	80	50	0	100	0	47	-2.48	forested	no	no
Lancaster	59	78	50	100	100	0	65	-1.6	residential	riprap	no
Lancaster	63	73	50	50	100	0	56	-0.24	forested	riprap	no
Mathews	64	83	50	50	100	0	58	-1.72	residential	groin	no
Lancaster	66	77	50	50	100	0	57	-2.58	forested	no	no
Lancaster	67	74	50	50	100	0	57	-2.88	forested	no	no
Lancaster	67	79	50	50	100	0	58	-2.53	forested	riprap	no
Mathews	70	88	50	50	100	0	60	-1.36	residential	groin	no
Lancaster	71	70	50	50	100	0	57	-2.78	forested	no	no
Mathews	71	89	50	50	100	0	60	-0.47	residential	bulkhead	no
Mathews	71	89	50	50	100	0	60	-0.34	residential	groin	no
Lancaster	72	76	50	0	100	0	38	-2.39	forested	riprap	groin
Mathews	77	91	50	50	100	0	61	-0.31	residential	groin	no
Mathews	77	96	50	50	100	0	62	-1.36	commercial	riprap	no
Mathews	84	95	50	50	100	0	63	-0.4	residential	groin	no
Mathews	86	92	50	50	100	0	63	0.11	residential	groin	no
Mathews	88	91	100	50	100	100	88	-3.31	commercial	no	riprap

APPENDIX II.

70-Location Final Model Calibration Data Set

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Essex	10	85	50	0	100	0	41	-1	residential	no	groin
Essex	10	87	50	50	100	0	50	-0.15	scrub-shrub	no	no
Essex	10	88	50	50	100	0	50	-0.03	residential	riprap	no
Middlesex	10	97	50	100	50	100	68	-0.9	residential	riprap	no
Essex	11	69	50	50	100	0	47	0.05	residential	bulkhead	no
Middlesex	11	92	50	100	50	0	51	-1.5	residential	no	no
Gloucester	11	92	50	50	100	0	51	-0.09	forested	no	riprap
Gloucester	11	95	50	50	100	50	59	-0.04	residential	no	no
Lancaster	11	97	50	50	100	0	51	-0.4	residential	bulkhead,groin	no
Mathews	12	93	50	50	100	50	59	0.69	residential	riprap	no
Gloucester	12	95	50	50	100	0	52	-0.07	residential	bulkhead	no
Mathews	13	91	50	50	50	0	42	-0.12	residential	no	groin
Mathews	13	94	50	100	50	0	51	0.23	residential	groin	no
Essex	13	96	50	0	100	0	43	0.03	scrub-shrub	no	no
Essex	14	79	50	100	100	0	57	-0.27	residential	bulkhead	no
Essex	14	85	50	100	50	0	50	-0.26	grass	riprap	no
Mathews	14	86	50	100	50	0	50	0	residential	riprap	no
Essex	15	82	50	50	100	0	50	-0.48	residential	groin	bulkhead
Mathews	15	84	50	100	100	50	67	-0.23	scrub-shrub	riprap	no
Essex	15	84	50	50	0	0	33	-0.43	residential	no	bulkhead,groin
Essex	15	84	50	50	0	0	33	-0.25	residential	bulkhead,groin	no
Essex	15	84	50	100	0	0	42	-0.27	residential	bulkhead,groin	no
Essex	15	85	50	100	0	0	42	-0.26	residential	bulkhead	no
Essex	15	86	50	50	0	0	34	-1.15	residential	riprap	no
Essex	15	90	50	0	100	0	43	-0.03	scrub-shrub	no	no
Mathews	16	83	50	100	100	100	75	-0.71	scrub-shrub	riprap	no
Mathews	16	88	50	100	100	50	67	-0.61	residential	groin	no
Lancaster	16	88	50	50	100	0	51	-0.1	residential	no	riprap,groin

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Mathews	16	94	50	50	100	50	60	0.87	commercial	no	riprap
Lancaster	17	88	50	50	100	0	51	-0.24	residential	groin	no
Essex	17	88	50	0	50	0	34	-0.28	residential	no	no
Lancaster	17	92	50	100	100	0	60	-0.07	scrub-shrub	no	no
Essex	19	81	50	50	100	0	50	-0.37	forested	no	no
Mathews	20	88	50	100	50	0	51	-0.33	residential	groin	no
Essex	20	88	50	50	100	0	51	-0.3	residential	groin	no
Lancaster	20	95	50	100	100	0	61	-0.95	residential	no	riprap,groin
Lancaster	23	87	50	100	0	0	43	-0.66	forested	riprap	no
Lancaster	23	92	50	100	100	0	61	-0.16	residential	riprap	no
Lancaster	23	95	50	50	100	0	53	-0.22	residential	riprap	no
Lancaster	24	90	50	0	100	0	44	0.31	residential	no	no
Lancaster	25	91	50	0	100	0	44	-0.79	residential	riprap,groin	no
Lancaster	26	93	50	50	100	0	53	-0.43	residential	groin	riprap
Lancaster	27	84	50	100	100	0	60	-1.04	residential	riprap	no
Lancaster	29	95	50	100	100	0	62	-1.28	residential	riprap,groin	groin
Lancaster	30	96	50	50	100	100	71	-1.1	commercial	no	groin
Gloucester	31	95	50	50	100	50	63	-0.3	residential	bulkhead	no
Gloucester	34	87	50	50	100	50	62	-0.14	forested	no	no
Gloucester	35	94	50	50	100	0	55	-0.28	residential	riprap	no
Gloucester	37	94	50	50	100	50	64	-0.28	residential	no	riprap
Gloucester	38	93	50	50	100	50	64	-0.12	residential	riprap	no
Lancaster	39	87	50	50	100	0	54	-1.08	scrub-shrub	no	no
Poquoson	46	82	50	50	100	0	55	-0.65	residential	riprap	no
Lancaster	48	69	50	0	100	0	45	-1.56	scrub-shrub	no	no
Lancaster	50	80	50	0	100	0	47	-2.48	forested	no	no
Lancaster	59	78	50	100	100	0	65	-1.6	residential	riprap	no
Lancaster	63	73	50	50	100	0	56	-0.24	forested	riprap	no

Model Calibration Data Set

Location	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Nearshore Morphology (%)	Bank Height (%)	Bank Cover (%)	Instability Factor (%)	Shoreline Change (%)	Land Use	Shoreline Armoring	Adjacent Armoring
Mathews	64	83	50	50	100	0	58	-1.72	residential	groin	no
Lancaster	66	77	50	50	100	0	57	-2.58	forested	no	no
Lancaster	67	74	50	50	100	0	57	-2.88	forested	no	no
Lancaster	67	79	50	50	100	0	58	-2.53	forested	riprap	no
Mathews	70	88	50	50	100	0	60	-1.36	residential	groin	no
Lancaster	71	70	50	50	100	0	57	-2.78	forested	no	no
Mathews	71	89	50	50	100	0	60	-0.47	residential	bulkhead	no
Mathews	71	89	50	50	100	0	60	-0.34	residential	groin	no
Lancaster	72	76	50	0	100	0	38	-2.39	forested	riprap	groin
Mathews	77	91	50	50	100	0	61	-0.31	residential	groin	no
Mathews	77	96	50	50	100	0	62	-1.36	commercial	riprap	no
Mathews	84	95	50	50	100	0	63	-0.4	residential	groin	no
Mathews	86	92	50	50	100	0	63	0.11	residential	groin	no
Mathews	88	91	100	50	100	100	88	-3.31	commercial	no	riprap

APPENDIX III.

22-Location Model Validation Data Set

Model Validation Data Set

Data Location (County)	Wave Power (%)	Nearshore Bathymetry (%)	Shoreline Exposure (%)	Instability Factor (%)	Shoreline Change (m/yr)
Essex	8	92	50	40	-0.18
Essex	8	87	50	38	-0.05
Essex	11	68	50	35	-0.08
Essex	6	57	50	30	-0.16
Essex	8	43	50	27	-0.14
Lancaster	14	85	50	41	-0.76
Lancaster	17	84	50	42	-0.59
Lancaster	17	90	50	44	-0.46
Lancaster	17	88	50	43	-0.11
Lancaster	17	86	50	43	-0.52
Mathews	94	86	100	94	-2.84
Mathews	97	87	50	83	-2.69
Mathews	50	85	50	59	-1.95
Mathews	48	87	50	58	-1.15
Mathews	48	87	50	58	-0.04
Mathews	48	83	50	57	-0.27
Middlesex	23	90	50	47	0.16
Middlesex	11	85	50	39	0.11
Middlesex	13	90	50	42	0.21
Middlesex	25	86	50	47	0.46
Middlesex	26	85	50	47	0.17
Middlesex	25	91	50	48	-0.42

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